

## Evaluation of Natural Attenuation South Cavalcade Superfund Site, Houston, Texas

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DATE: March 30, 2011

### Summary

Monitored Natural Attenuation (MNA) is being considered as the final component of the overall remedy to address the dissolved phase groundwater contamination at the South Cavalcade Superfund Site. The South Cavalcade Superfund Site is a 66-acre former wood treating site located in Houston, Harris County, Texas. Wood treating at the Site was conducted from 1910 to 1962, primarily using creosote as a preservative. Also, a coal tar distillation facility operated at the Site from 1942 to 1962. This “Technical Memorandum: Evaluation of Natural Attenuation” provides various lines of evidence to demonstrate that natural attenuation (NA) is an effective groundwater remedy for the remaining impacts at the South Cavalcade Site.

Constituents of Interest (COIs) for the Site are Polynuclear Aromatic Hydrocarbons (PAHs) and benzene, toluene, ethylbenzene, and xylenes (BTEX). The primary indicator constituents for this NA evaluation are benzene and naphthalene given that they are the most mobile of the creosote-related constituents. The natural biodegradation of these constituents in groundwater is well documented in the peer-reviewed scientific literature. The evaluation presented herein supports the use of NA for the Site based on consideration of multiple lines of site-specific evidence including:

*Temporal changes in benzene and naphthalene concentrations* – Analytical results for the downgradient wells are clearly indicative of stable conditions. Concentrations are consistent or declining over time.

*Geochemical monitoring data for NA indicator parameters* – Geochemical “footprints” indicate that conditions are more reduced in the core of the plume than on the exterior. Consumption of sulfate electron acceptor and production of ferrous iron and manganese within the plume core are indicative of microbiological activity.

*Fate and transport modeling* – Analytical modeling demonstrates that biodegradation is controlling the extent of dissolved constituents in groundwater. The actual plume lengths are much shorter, and actual concentrations much less than what would exist if there were no biodegradation occurring.

*An estimate of the assimilative capacity of the biological components of NA* – Mass budgeting analysis indicates that the assimilative capacities in the aquifer in the North and South Areas of the Site average 16 mg/l and 25 mg/l, respectively. Based on the other assessments performed as part of this evaluation, it is evident that these assimilative capacities are sufficient to stabilize the dissolved phase plumes.

*Evidence of active microbiological populations within the contaminant plume* – Biomass in solid samples within the plume is more than an order of magnitude greater than outside of the plume which is indicative of an elevated level of bioactivity within the impacted portions of the aquifer. Moving forward, the next steps to take for implementation of the NA alternative are to finalize the FFS, the Human Health Risk Assessment, and the Technical Impracticability demonstration. Upon completion of these activities, a Proposed Plan and (following public comment on the Proposed Plan) an amendment to the ROD incorporating MNA as the preferred remedial alternative will be prepared.

In consideration of the multiple lines of evidence that have been developed for the South Cavalcade Site and the conclusion that MNA is feasible for both Shallow and Interbedded Zone groundwater, it is recommended that an appropriate monitoring program be implemented. The objective of the MNA monitoring program would be to provide ongoing confirmation that MNA is effectively addressing Site constituents, and allow for early detection of potential trends or evidence indicative of additional COI migration (if any). A conceptual monitoring program is presented in Section 6.0. Additional details on the proposed monitoring program will be presented in the Proposed Plan. As part of the Remedial Design process, a groundwater monitoring plan will be prepared that will include all of the specific requirements for the groundwater monitoring program.

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## **1.0 Introduction**

This technical memorandum provides an evaluation of the natural attenuation (NA) processes occurring at the South Cavalcade Superfund Site in Houston, Texas (Site). This evaluation provides a basis for deciding if a MNA program can be used as an effective remedy for groundwater at the Site. If an MNA remedy is determined to be feasible and appropriate, an amendment to the Record of Decision (ROD) will be prepared to document the change to the remedy for the Site.

## **1.1 Background**

The South Cavalcade Superfund Site is a 66-acre former wood treating site located in Houston, Harris County, Texas. Koppers Company, Inc. (Koppers, now known as Beazer) operated a wood treating plant at the Site from 1910 until 1962, primarily using creosote as a preservative. A coal tar distillation plant was also operated on the southeastern portion of the property from 1944 until 1962. At the current time, the southern portion of the property is utilized by two trucking firms, the northern portion is not used, and much of the property is either paved or under roof.

The original Record of Decision (ROD) for the site issued on September 26, 1988 (USEPA, 1988) required a remedy to address both impacted soil and groundwater. In addition, it required that Dense Non-Aqueous Phase Liquid (DNAPL) present in the subsurface be addressed. The remedial components required by the ROD for soil and groundwater had been initiated as of 1995.

As part of the amended remedy for soil, impacted soils were excavated and consolidated in the Southeast and Southwest portions of the property. These areas were capped with concrete in 1999 in view of anticipated land use (trucking companies) and as an engineering control. The cap prevents potential risks associated with dermal contact with potentially impacted soils. Additionally, the Administrative Order on Consent between the USEPA and the landowners require that the existing paving be maintained.

Pursuant to the conditions of the Record of Decision, DNAPL and shallow groundwater was initially addressed using an extraction and treatment system which was to be operated until constituents were recovered to the extent practical. The ROD also indicated that active collection would cease once recovery was completed to the extent practical and stipulated that remaining constituents would be allowed to naturally attenuate.

The groundwater remedial action addressed three separate Groundwater Remedial Action Areas (GRAAs). The remedy consisted of the use of DNAPL recovery wells and groundwater collection and treatment. These components were constructed in the Spring and Summer of 1995. Shortly thereafter, the USEPA adopted a policy accommodating Applicable or Relevant and Appropriate Requirement (ARAR) waivers at sites where it is technically impracticable to remediate groundwater to Federal or state standards. Subsequently, the USEPA and Beazer agreed to delay any additional active groundwater collection and treatment while alternate remedial approaches were evaluated because of the impracticability of meeting drinking water standards. However, the parties agreed that DNAPL recovery would be implemented while the alternative approaches were evaluated.

In 1997, Beazer submitted a Groundwater Fate and Transport Evaluation Report (GFTER) to the USEPA in which the results of an extensive groundwater modeling effort were presented (KEY, 1997). The results presented in the GFTER supported a preliminary hypothesis that NA of the dissolved organic constituents of interest was occurring and that DNAPL migration in the subsurface has ceased.

In 2000, Beazer submitted a Verification of the Groundwater Fate and Transport Evaluation Report (VGFTER), which supported the conclusion that MNA is a feasible alternative for the residual DNAPL and the dissolved constituents at the site (KEY, 2000). Stable DNAPL and dissolved phase conditions were demonstrated based on fate and transport analysis, consideration of constituent concentrations as a function of time, NA indicator parameter information, and evidence of microbial activity (phospholipid fatty acid information).

Since the construction of remedial components, two Five-Year reviews have been completed which conclude that the remedies remain protective for current Site conditions. These Five-Year Reviews are dated September 2002 and September 2007 (USEPA, September 2002 and USEPA, September 2007). Ongoing activities at the Site include quarterly passive DNAPL recovery, annual groundwater monitoring, and annual cap inspection.

The DNAPL recovery operations were initiated in September 1995 with the start-up/shakedown of the recovery system. Subsequent to the start-up/shakedown period, passive DNAPL recovery was initiated in January 1996. DNAPL was recovered using four wells which were installed in areas exhibiting the presence of potentially recoverable DNAPL. These areas corresponded to topographic lows in the upper surface of a basal confining unit co-located with former plant process areas believed to be potential DNAPL source areas (PDSAs).

Enhanced or active DNAPL recovery (i.e., aided by the extraction of groundwater) was initiated in October 1996. This operation continued until April 2006 when a lightning strike in 2006 disabled the groundwater treatment system. The DNAPL recovery rate had declined by this time and passive recovery was subsequently implemented via quarterly removal of DNAPL from the wells. Recovery rates were always low even with groundwater pumping and were highest in 1998 and 1999 (1.92 gallons per day [gpd]) and had declined to 0.84 gpd by the time groundwater pumping was discontinued in 2006. Recent passive DNAPL recovery rates were 0.017 gpd in 2009 and 0.0 gpd in 2010. To date, the recovery system has collected approximately 4,000 gallons of product (creosote) from the shallow sand water-bearing unit as shown in Figure 1-1.

Based on the consideration of DNAPL recovery information collected over approximately 15 years, and analytical data collected over approximately 20 years, it has been concluded that the DNAPL is no longer migrating via preferential pathways, and that the dissolved constituents' behavior is consistent with NA (i.e., constituent concentrations are stable or declining).

## 1.2 Natural Attenuation Evaluation Approach

NA processes affect the fate and transport of contaminants in groundwater. Mechanisms for *in situ* NA of contaminants in groundwater include biodegradation (aerobic and anaerobic), adsorption, advection, dispersion, volatilization, and other abiotic reactions. NA processes occur at all sites, but to varying degrees of effectiveness depending on the types and concentrations of contaminants present and the physical, chemical, and biological characteristics of the soil and groundwater. NA processes may reduce the potential risk posed by site contaminants in three ways (USEPA, 1999):

- (1) Transformation of contaminant(s) to a less toxic form through destructive processes such as biodegradation or abiotic transformations;
- (2) Reduction of contaminant concentrations whereby potential exposure levels may be reduced; and
- (3) Reduction of contaminant mobility and bioavailability through sorption onto the soil or rock matrix.

These processes have been shown at many sites worldwide to provide a significant contribution to the remediation of site contaminants and thereby reduce or eliminate the burden on active remediation systems. As such, at many sites MNA provides a cost-effective and more environmentally sustainable method of attaining RAOs.

As described herein, MNA is not considered a "no action" or "walk-away" approach, but rather an alternative means of achieving remedial action objectives that may be appropriate for specific, well-documented site circumstances where its use meets the applicable statutory and regulatory requirements. The term MNA refers to the reliance on NA processes (within the context of a carefully controlled and monitored site cleanup approach) to achieve site-specific remediation objectives within a time frame that is reasonable compared to that offered by other more active methods (USEPA, 1999).

This NA evaluation uses a three-tiered approach to evaluate the efficacy of MNA at the site. As recommended by USEPA guidance (USEPA, 1999), successively more detailed information is collected as necessary to provide an acceptable level of confidence in both the understanding of attenuation processes and the anticipated time required to achieve remediation objectives. These three tiers of information, or "lines of evidence", are:

- (1) Historical groundwater chemistry data that demonstrate a clear and meaningful trend of stable or decreasing COI mass and/ or concentration over time at appropriate monitoring or sampling points. Concentrations of COIs are evaluated to determine if there has been any change in the concentration and distribution of the contaminants over time. Stable or decreasing concentrations over time suggests that NA is actively controlling and degrading the COIs.
- (2) Hydrogeologic and geochemical data that can be used to demonstrate the type(s) of NA processes that may be active at the Site, and the rate at which such processes will reduce contaminant concentrations to required levels. Geochemical conditions are

evaluated to identify oxidation-reduction (redox) states and which terminal electron-accepting processes (TEAPs) are acting on portions of the contaminant plume.

- (3) Microbial data which may include field or microcosm studies conducted in or with actual impacted Site media which directly demonstrate the occurrence of a particular NA process at the Site and its ability to degrade the contaminants of concern (typically used to demonstrate biological degradation processes only). These data may also include microbial ecology (e.g., phospholipid fatty acids (PFLA)), which is examined to determine if contamination is stimulating indigenous microorganisms.

Numerical modeling or conservative analytical models are often also used to predict the fate and transport of Site COIs including anticipated impacts to potential receptors and restoration timeframe.

In general, affirmation of only one of these lines of evidence would be insufficient to demonstrate the efficacy of MNA at the Site. However, the agreement of several observations ("converging lines of evidence") can provide an acceptable level of confidence in the efficacy of MNA as a remedy for groundwater at the Site.

### **1.3 Document Layout**

This report is divided into the following sections:

Section 1 - Introduction - describes the goals and organization of the report.

Section 2 - Conceptual Site Model- summarizes the hydrogeology of the Site, the nature and extent of indicator COIs at the Site, unique features at the Site that affect the fate and transport of COIs at the Site, and a summary of the exposure and risk assessment.

Section 3 - Biodegradation of Site COIs - describes potential biodegradation processes and mechanisms that may affect the Site COIs using benzene and naphthalene as examples.

Section 4 - Site-Specific Lines of Evidence - describes COI plume stability, geochemical footprints, mass budgeting and assimilative capacity analysis, microbiological assessment, and fate and transport modeling results.

Section 5 - Summary of Efficacy of MNA - summarizes and integrates the converging lines of evidence supporting the efficacy of MNA, discusses restoration time frame, and specifies the uncertainties that exist in the evaluation.

Section 6 – Path Forward - recommends future activities, including ongoing field sampling efforts to confirm the effectiveness and rate of MNA at the Site.

## **2.0 Conceptual Site Model Development**

The nature and extent of contamination at the South Cavalcade Site has been documented through sampling of various environmental media since the mid-1980s, beginning with a Remedial Investigation/Feasibility Study (RI/FS) which was completed and submitted to the USEPA in 1988 (Keystone Environmental Resources, 1988a and 1988b). As a result of the RI/FS, a ROD was ultimately issued by the USEPA (September 1988). In 1991, Beazer entered into a Consent Decree with the USEPA to implement the Remedial Design/Remedial Activities specified in the ROD and a Remedial Design Work Plan was prepared (Bechtel, March 1992).

By late 1993, contractors had completed pilot studies to support the groundwater remedial design (McLaren/Hart, December 1994), which was ultimately approved by the USEPA. The groundwater remedial design provided for groundwater collection and DNAPL recovery in three separate Groundwater Remedial Action Areas. Implementation began in 1995 and included the use of DNAPL recovery wells and low flow groundwater collection wells to recover DNAPL and dissolved phase constituents.

While DNAPL has been observed in both the shallow sand zone (herein referred to as the Shallow Zone) and in an underlying intermediate zone (herein referred to as the Interbedded Zone to maintain consistency with the nomenclature for the adjacent North Cavalcade Site). DNAPL recovery was not attempted from the Interbedded Zone as a result of concerns regarding the potential for inducing vertical migration of DNAPL from the Shallow Zone. In addition, it was determined that migration to the deeper Interbedded Zone likely occurred through uncased boreholes that perforated the Shallow Zone and through poorly sealed monitoring wells. These poorly constructed wells have since been abandoned and replaced with new, properly installed deep monitoring wells. No additional releases are occurring given that wood treating and coal tar distillation operations ceased in the 1960s.

Downgradient monitoring wells have shown stable or declining time-dependent constituent concentrations since the initial Site investigations. The primary areas of concern consist of the Shallow Zone and Interbedded Zone in two localized DNAPL impacted areas hereinafter referred to as the North Area and the South Area. Dissolved phase plumes exist which attenuate within a short distance of these source areas. A narrow stringer of DNAPL extends offsite in the South Area, most likely as a result of discharges to a historic drainage feature in the area of interest. The DNAPL and dissolved phase constituents associated with this stringer are also attenuated in a short distance and appear to be stable or declining based on available data.

Active and passive DNAPL recovery has been conducted since 1995 and has resulted in removal of over 4,000 gallons of DNAPL. No evidence of downward vertical migration below the Interbedded Zone has been observed. The Interbedded Zone is underlain beneath the Site by a massive clay layer. This clay layer prevents downward migration of DNAPL and acts as a confining layer to separate groundwater in the Shallow and Interbedded Zones from the deeper regional groundwater regime. The Interbedded Zone pinches out into this clay downgradient of the potential DNAPL source areas.



Sections 2.1 and 2.2, respectively, provide a summary of the lithology/hydrogeology and the nature and extent of contamination as depicted in numerous investigation reports submitted since 1988.

## **2.1 Lithology/Hydrogeology**

The South Cavalcade Site is located in the Southeast Texas Coastal Plain. This region is underlain with Holocene and Pleistocene deposits to a depth of approximately 2,400 feet. Groundwater used to supply water for domestic, industrial, and agricultural purposes is pumped from the Lower Chicot and Evangeline aquifers from depths ranging from about 100 feet to more than 2000 feet.

Figures 2-1 through 2-3 present geologic cross-sections prepared to illustrate the geologic conditions at the Site. The geology at the Site consists of interbedded clays, silts, and sands of fluvial-deltaic origin overlain by discontinuous fill. The primary surficial water-bearing units at the Site are a shallow sand zone and an underlying, discontinuous interbedded zone. The groundwater contamination observed at the Site is limited to these two units; thus, the discussion of Site hydrogeology will focus primarily on these units and the associated aquitards.

The Shallow Sand Zone consists of a layer of fine sand, silty sand and clayey sand that extends from the ground surface to a depth of about 17 to 22 feet below ground surface (bgs). The upper half of this unit consists of sandy or silty clay deposits, while the lower portion has a greater proportion of sand and is referred to as the “Shallow Zone”. In the southern portion of the Site, the unit pinches out. Groundwater flow is generally in a westerly direction, as shown in Figure 2-4. The Shallow Zone is underlain by a layer of predominantly silt and clay, approximately 100 feet thick. Within this aquitard are several more distinct units. The uppermost portion of the aquitard consists of about 20 feet of clay-rich materials that act as the basal confining unit for the Shallow Zone. At a depth of about 40 to 50 feet bgs lies discontinuous silty sands, herein referred to as the “Interbedded Zone”, previously identified as the “intermediate zone” in the RI/FS and Remedial Design. The terminology “Interbedded Zone” was adopted to provide consistency with the North Cavalcade Technical Memorandum submitted in 2010 (CH2M-HILL, 2010).

The Interbedded Zone is composed of thin, interbedded clay, silt, and sand layers that are saturated. Where present, the Interbedded Zone consists of between 5 and 15 feet of sand or silty sand. Groundwater flow direction in the Interbedded Zone is also generally in a westerly direction, as shown in Figure 2-5. The hydraulic connection between the two water-bearing zones appears to be negligible, based on results of pumping tests and measurements of potentiometric surfaces in the two zones (KEY, 2006). Beneath the Interbedded Zone lie approximately 80 additional feet of clay, which act as a basal confining unit for the overlying, discontinuous silty sand aquifer (Interbedded Zone). This thick clay acts as a barrier to further downward migration of DNAPL. Analytical data from the RI demonstrate that impacts have not penetrated this unit.

The Shallow Zone is easily identifiable on boring logs for the Site. The Shallow Zone is predominantly fine-grained sand. The upper portion is most frequently classified as a silty sand (USCS symbol SM) or clayey sand (SC). The top of the Shallow Zone generally occurs between

10 and 15 ft bgs, and the base of the Shallow Zone generally occurs between 20 and 25 ft bgs. The thickness of the Shallow Zone ranges from approximately 0 to 20 ft across the Site. The variation in thickness is typical of a fluvial-deltaic depositional environment. The Shallow Zone is discontinuous at the southwestern corner of the property.

The Interbedded Zone consists of saturated, interbedded lean clay (CL), silty clay/clayey silt (CL/ML), lean silt (ML), clayey sand (SC), silty sand (SC), and poorly graded sand (SP). Some of the boring logs do not show any discrete sand or silt layers to label as the Interbedded Zone. In some cases, lenses of silt and sand are noted within the clays in the interval where the Interbedded Zone occurs. The Interbedded Zone is separated from the shallow sand zone by a layer of fat clay (CH) and lean clay (CL) identified as the Intermediate Aquitard (see Figures 2-1 through 2-3). The top of the Interbedded Zone generally occurs between 30 and 40 ft bgs, and the base of the Interbedded Zone generally occurs between 50 and 55 ft bgs. The thickness of the Interbedded Zone ranges from approximately 2 to 20 ft across the Site.

Migration of COIs in the Interbedded Zone in the northern portion of the Site is impeded by the thinning and pinching out of the unit. Migration of COIs in other portions of the property and in the Shallow Zone in the southern portion of the Site may also be impeded by the increasingly more clayey materials to the west. Thus the mobility of the dissolved constituents is reduced as a result of the reduction in permeability and/or limited downgradient extent of the two more permeable water-bearing zones.

## **2.2 Nature and Extent of COIs**

The COIs identified at the Site are polycyclic aromatic hydrocarbons (PAHs) and benzene, toluene, ethylbenzene, and xylenes (BTEX). These are typical COIs for creosote wood treating sites. COIs observed in groundwater originate from creosote in the subsurface, which occurs as a DNAPL. Various observations and measurements were used to define the extent of the “potential DNAPL source areas (PDSAs)” in the Shallow Zone and the Interbedded Zone, as well as in the Intermediate Aquitard lying between the two water-bearing zones. Primarily visual observation was used during the logging of boreholes, but this information was supplemented with chemical analytical data for both soil and groundwater. The PDSAs are presented on Figures 2-6 (Shallow Zone), 2-7 (Intermediate Aquitard) and 2-8 (Interbedded Zone).

Annual groundwater monitoring for deeper water-bearing zones (i.e., the “200-foot sand” and a unit approximately 500 feet below ground surface [bgs]) indicates that these deeper units have not been impacted. Information from the Remedial Investigation demonstrates that impacts are attenuated just below the base of the Interbedded Zone and well above these units at an approximate maximum depth of 70 feet bgs.

Comparison of the three source area figures indicates that the estimated DNAPL footprints are similar in the three units (Shallow Zone, Intermediate Aquitard and Interbedded Zone). In the northern area of the Site, the figures indicate two areas of DNAPL occurrence. The northernmost occurrence generally corresponds to a former pond area.

Two areas of potential DNAPL occurrence are also delineated in the Interbedded Zone in the southern area of the Site, although they are connected in the Intermediate Aquitard and Shallow Zone. These areas correspond to the former wood treating process area near the southern Site boundary, and to the former coal tar plant along the eastern boundary. Table 2-1 presents a summary of the measured DNAPL thicknesses and the associated well in which the observation was made for both the Shallow Zone and the Interbedded Zone (KEY, 2008).

**Table 2-1**  
**Apparent DNAPL Thickness**  
**South Cavalcade Superfund Site**  
**Houston, Texas**

Well	Apparent DNAPL Thickness (ft)			Date (Most Recent)	Comments
	Minimum	Maximum	Most Recent		
Shallow Zone Wells					
RWS-1	0	10.93	0.02	12/18/06	
RWS-2	0	3.59	2	12/18/06	
RWN-4	0	11	0	08/30/06	
RWS-5	0	2.73	0.05	11/29/06	
PZS-10	0	6.67	0	10/17/06	
PZS-20	0.083	13	3.96	10/17/06	
PZN-40	0	Trace	0	10/17/06	Trace during historical sampling
PZN-41	0	Trace	0	10/17/06	Trace during historical sampling
PZS-50	0.08	0.62	0.26	10/17/06	
PZS-51	0	0.25	0	10/17/06	
OW-02	0	2.42	0.07	10/17/06	
OW-10	0	Trace	0	10/17/06	Trace during historical sampling
OW-11	0.683	0.98	0.1	10/17/06	
P-02N	-	0.8	0.8	09/17/05	One available measurement
MW-06	0	3	0	09/17/05	
Interbedded Zone Wells					
OW-20	-	1.27	1.27	09/16/05	One available measurement
MW-12R	-	2	2	09/17/05	One available measurement
ITW-02	-	2.4	2.4	09/17/05	One available measurement

No known releases of DNAPL have occurred since wood treating operations ceased at the Site in 1962. No DNAPL expansion or contraction has been observed since sampling and analysis activities have begun.

Benzene and naphthalene were selected as indicator parameters for both the DNAPL and the dissolved phase constituents found in the subsurface. These two are among the most common and soluble of their respective creosote compound groups (BTEX and PAHs) and therefore tend to be the most mobile of the COIs. Subsequently, benzene and naphthalene are used to define the extent of impacts at the South Cavalcade Site.

COIs dissolve from the source zone DNAPL into groundwater as a function of the effective solubilities of the individual compounds. Migration of dissolved phase COIs occurs, primarily in the direction of groundwater flow, as a result of physical processes (dispersion, diffusion, and advection). Attenuation mechanisms such as dilution as a result of recharge, dispersion, adsorption, and biodegradation cause COI concentrations to decrease with increasing distance from the source. Additional limiting properties that affect COI migration include hydraulic conductivity and hydraulic gradient, as well as the lateral extent of the water-bearing units.

Two figures (2-9 and 2-10) have been prepared showing the most recent concentrations of dissolved naphthalene and benzene in the Shallow and Interbedded Zones, respectively. The figures show that concentrations of the indicator COIs (benzene and naphthalene) are most pronounced within and immediately downgradient of the source zone DNAPL areas and that they decrease significantly in the downgradient direction over a relatively short distance. Assessments done as part of the GFTER (KEY, 1997) show that in the absence of NA, the distribution of dissolved phase COIs in groundwater would be much more extensive than the observed conditions. Thus, these groundwater quality data are a direct indication of effective attenuation in the subsurface in close proximity to the PDSAs as a result of a combination of physical, chemical, and biological processes.

### **2.3 Potential Exposure Pathways**

The Shallow Zone and the Interbedded Zone are not being currently used as sources of drinking water onsite or within a one-mile radius of the Site (onsite use of groundwater is prohibited by the January 24, 1992 Administrative Order on Consent between the USEPA and the property owners). In an effort to confirm the location and depth of completion of existing water wells within the vicinity of the Site, a water well search was conducted to identify all water wells within a one and two mile radius of the South Cavalcade Site. A detailed discussion of the results of the well search was included in the VGFTER (KEY, 2000). Results of the water well search confirmed that no shallow water wells are located within one to two miles of the South Cavalcade Site. The closest water wells to the Site are approximately 500 feet northeast and southeast (i.e. upgradient) of the Site and are about 300 feet deep. Water from these wells is reportedly for domestic and industrial use (KEY, 2000).

The Houston Galveston Coastal Subsidence District (HGCSD) requires notification and permits for the drilling of new groundwater wells, discouraging the use of private wells in those areas adequately served by the City of Houston municipal water supply system (CH2M-HILL, 2008). In addition, iron and manganese are present in the shallow groundwater at background concentrations that exceed drinking water criteria and an extraction well pilot study performed for the Site indicated that the shallow aquifer could not sustain a flow higher than 2 gallons per minute, thereby precluding any uses that have higher production demands (KEY, 2000). As a result of all of these factors, it is unlikely that there would be any future receptors with respect to shallow groundwater.

Water use and geologic information also demonstrates that potential exposure via use of deeper groundwater is also extremely unlikely. While regional geologic information indicates that a deep onsite aquifer exists, which is potentially useable as a public water supply source, onsite businesses and neighboring residents are served by the City of Houston water supply which

originates from a deeper aquifer 10 miles from the Site, or a surface water reservoir located over 20 miles from the Site. The closest City of Houston supply wells are located hydraulically upgradient of the Site with respect to the shallow groundwater flow.

Groundwater used to supply water for domestic, industrial, and agricultural purposes in Harris County is pumped from the Lower Chicot and Evangeline aquifers. Both of these aquifers are confined and isolated from surface recharge. Public water supply wells are screened in the Evangeline aquifer at depths greater than 600 feet bgs (CH2M-HILL, 2010). Domestic and industrial water supply wells in the vicinity of the South Cavalcade Site are typically screened at depths of between 150 and 500 feet below ground surface because the Shallow and Interbedded Zones have an unreliable, low yield. Municipal supply wells are much deeper, being screened at depths of 1000 feet or more (KEY, 2000). A similar survey performed for the North Cavalcade Site reported similar results, with industrial water users in the general area having wells screened in both aquifers at depths ranging from 100 to 576 feet (CH2M-HILL, 2008).

Finally, because the stratigraphy at the Site, as recorded during the installation of a deep monitoring well showed the presence of approximately 127 feet of lean and fat clay (CL or CH) underlying the impacted groundwater zone, downward migration beyond the Interbedded Zone is improbable. Two deep wells have been installed downgradient of, and as near as possible to, the impacted Shallow and Interbedded Zones, without the possibility of creating a potential conduit for cross-contamination of the deeper groundwater. Analyses of groundwater samples collected from these wells have consistently shown non-detectable levels of creosote constituents. Therefore, it can be said with certainty that there is no potential pathway through which the DNAPL or the impacted groundwater on Site can migrate to aquifers that are used for water supply. Hence, no potential current or future receptors have been identified for the affected subsurface soil and groundwater.

### **3.0 Biodegradation of Site Contaminants**

Biodegradation can play a significant role in abating and detoxifying contaminants in groundwater. In some instances, these natural degradation processes alone might be sufficient to meet the RAOs for the Site. This section discusses the various possible aerobic and anaerobic biodegradation pathways for benzene and naphthalene in groundwater at the Site. The following information was compiled by CH2M-HILL for the North Cavalcade Site Technical Memorandum and is directly applicable to the South Cavalcade Site as well.

#### **3.1 Biodegradation of Benzene**

Biodegradation of benzene can occur under both aerobic and anaerobic conditions, and *in situ* bioremediation is being applied increasingly for aquifer treatment at petroleum hydrocarbon contaminated sites. For MNA, anaerobic biodegradation may be a more prominent mechanism than aerobic processes. Aerobic bioremediation process requires adequate oxygen supply that typically persists at the plume periphery but may be exhausted in the plume core at sites containing a large mass of DNAPL such as creosote. In contrast, anaerobic processes have advantages such as low biomass production and natural electron acceptor availability (e.g., sulfate). At times, anaerobic processes are the most cost-effective remedy for active bioremediation because it is often difficult to sustain elevated oxygen concentrations in source zones (Farhadian et al., 2008). For NA both aerobic and anaerobic biodegradation are expected

to occur at contaminated sites with mixed oxidation/reduction (redox) conditions such as those observed at this Site.

In the process of aerobic cometabolism of benzene, benzene is converted to catechol first through oxidation of the aromatic ring via a mono oxygenase or dioxygenase attack. Then the ring cleavage occurs by catechol 2,3-dioxygenases (Hendrickx et al., 2006). Rapid benzene biodegradation under natural aerobic conditions was observed in a field study, and it appeared that oxygen supply was the factor limiting benzene degradation. No biodegradation occurred under anaerobic conditions except when nitrate was provided as a terminal electron acceptor for microbial respiration. Degradation under denitrifying conditions occurred at a much slower rate than under oxygenated conditions (Morgan et al., 1993).

Anaerobic biotransformation of benzene has been demonstrated under iron-reducing (Jahn et al., 2005), sulfate-reducing (Abu Laban et al., 2009, Anderson and Lovley, 2000, Jin et al., 2007), and manganese-reducing conditions; and most of the benzene was mineralized to carbon dioxide (CO<sub>2</sub>) (Foght, 2008). There is limited evidence of benzene biodegradation under methanogenic conditions (Grbicgalic and Vogel, 1987). Historically, benzene was known as recalcitrant under denitrifying conditions, but benzene biodegradation linked to nitrate reduction was demonstrated in enrichment cultures, with CO<sub>2</sub> as the predominant end product (Burland and Edwards, 1999). Nonetheless, benzene oxidation under denitrifying conditions appear to be site-specific and unpredictable; its degradation under these conditions may rely on the presence of specific microorganisms capable of initiating attack on benzene rather than those metabolizing the oxidized intermediates, since intermediates like benzoate are readily degraded under all terminal electron acceptor process (TEAP) conditions (Foght, 2008).

The most plausible transformation pathways of anaerobic benzene biodegradation are i) hydroxylation to form phenol, cyclohexanone, or p -hydroxybenzoate and benzoyl-CoA; ii) alkylation to form toluene, followed by fumarate addition to form benzyl succinate and benzoyl-CoA; or iii) carboxylation to form benzoate and benzoyl-CoA. Benzoyl-coA, a central intermediate in anaerobic oxidation of aromatic compounds, can eventually be oxidized to acetyl-CoA and CO<sub>2</sub> (Foght, 2008).

Anaerobic biodegradation of benzene under sulfate-reducing conditions appeared to be more favorable than under other anaerobic conditions, such as methanogenic or iron-reducing conditions (Anderson and Lovley, 2000). Under sulfate-reducing conditions, detection of benzoate as an intermediate product supported that a direct carboxylation of benzene was the initial activation mechanism, and benzene was anaerobically oxidized to CO<sub>2</sub> (Abu Laban et al., 2009, Vogt et al., 2007). A column study observed that benzene oxidation rates fell in the range of 8-36  $\mu\text{mol/day}$  (i.e., up to 2.8  $\text{mg/L/day}$ ), however, the actual transformation rate observed on site was much lower (Vogt et al., 2007). Research indicated that elevated sulfide concentrations from sulfate reduction is a limiting factor to benzene biodegradation and ferric chloride (FeCl<sub>3</sub>) addition to groundwater may be a simple remedy to mitigate this problem and enhance benzene biodegradation by the indigenous sulfate-reducing bacteria population (Jin, et al., 2007). Some reported information on the first order rate constants and half lives of benzene biodegradation under various conditions are presented in Attachment 1. The half life of benzene biodegradation under anaerobic conditions varies from tens to hundreds of days.



### 3.2 Biodegradation of Naphthalene

*In situ* bioremediation of naphthalene was widely reported under aerobic conditions (Bakermans et al., 2002, Baldwin et al., 2009, Dominguez et al., 2008, Durant et al., 1999, Ebihara and Bishop, 2002, Nebe et al., 2009, Nyssonen et al., 2009, Tiehm and Schulze, 2003) and denitrifying and sulfate-reducing conditions (Aitken et al., 2004, Bakermans et al., 2002, Bamforth and Singleton, 2005, Durant et al., 1999, Griebler et al., 2004, Hunkeler et al., 1998, Maillacheruvu and Pathan, 2009, Meckenstock et al., 2004b, Rothermich et al., 2002, Tiehm and Schulze, 2003). Anaerobic biodegradation of naphthalene was incomplete under manganese-reducing conditions, and was not reported under methanogenic or iron-reducing conditions (Foght, 2008).

The principal mechanism for the aerobic bacterial metabolism of naphthalene is the initial oxidation of the benzene ring by the action of dioxygenase enzymes to form cis-dihydrodiols. These dihydrodiols are dehydrogenated to form dihydroxylated intermediates, which can then be further metabolized via catechols to CO<sub>2</sub> and water (Figure 3-1). There is a large variety of bacteria able to oxidize naphthalene using dioxygenase or mono oxygenase enzymes, such as organisms from the genus *Pseudomonas* and *Rhodococcus*, and methanotrophic bacteria (Bamforth and Singleton, 2005).

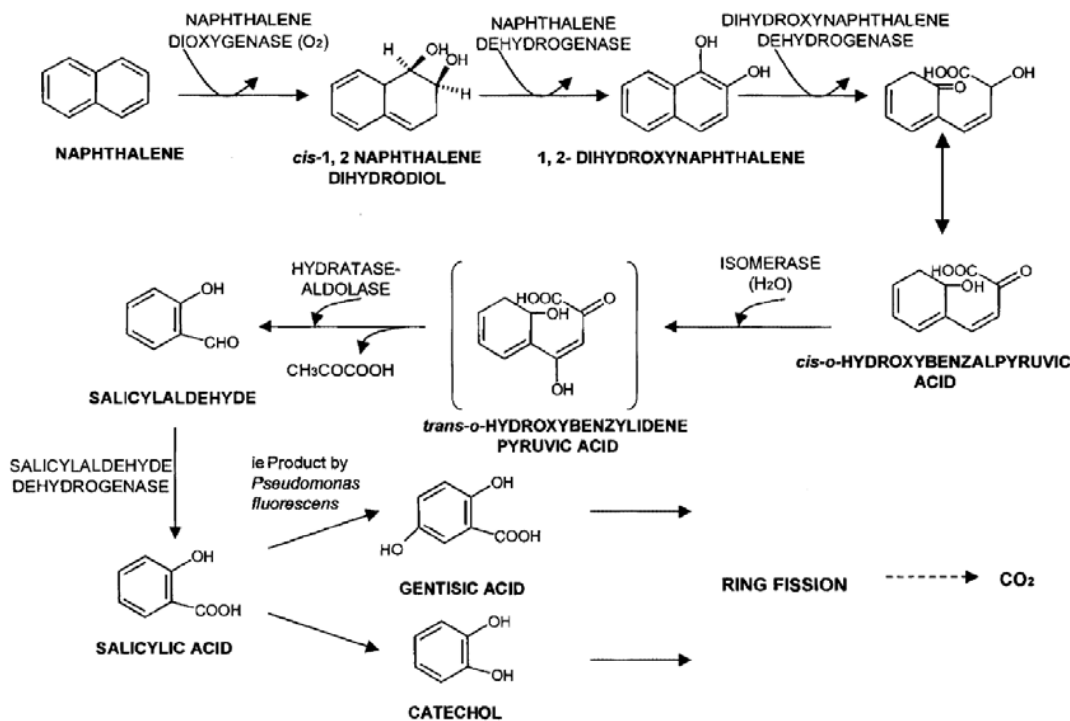


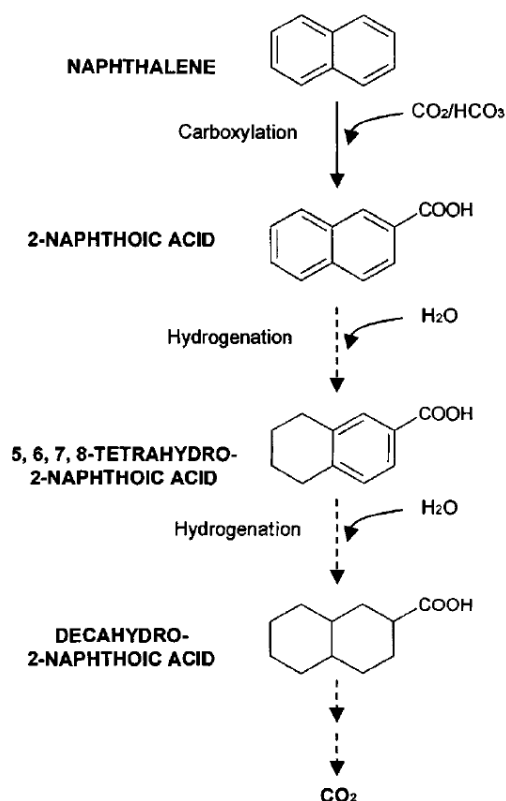
Figure 3-1

The main pathways in the aerobic degradation of naphthalene by bacteria (Bamforth and Singleton, 2005)

The mechanisms of anaerobic naphthalene degradation are still tentative, though recent studies supported a carboxylation pathway under sulfate-reducing conditions (Zhang et al., 2000) (Figure 3-2). The first step is carboxylation of the aromatic ring to 2-naphthoic acid, which may activate the aromatic ring prior to hydrolysis. Stepwise reduction of 2-naphthoic acid eventually



converted to decahydro-2-naphthoic acid, which is then mineralized to CO<sub>2</sub> (Bamforth and Singleton, 2005). It was widely demonstrated that mineralization of naphthalene to CO<sub>2</sub> was the dominating process under sulfate-reducing conditions (Coates et al., 1996, Rothermich et al., 2002, Selesi and Meckenstock, 2009). Although naphthalene usually degrades faster than larger PAHs, a distinct exception in Boston Harbor sediment was naphthalene that was degraded very slowly at a rate comparable to larger PAHs (Rothermich et al., 2002). Therefore, the biodegradation rates of naphthalene are likely highly site-specific. Temperature, pH, redox conditions, nutrient availability, and bioavailability (i.e., availability of naphthalene-degrading microbes) are factors affecting biodegradation of naphthalene (Bamforth and Singleton, 2005).



**Figure 3-2**

Simplified proposed pathway for the anaerobic metabolism of naphthalene under sulfate-reducing conditions (Bamforth and Singleton, 2005)

Some reported information on the first order rate constants and half lives of naphthalene biodegradation under various conditions are presented in Attachment 1. The half life of biodegradation of naphthalene under anaerobic conditions varies from hundreds to thousands of days.

#### 4.0 Site-Specific Lines of Evidence

Consistent with the OSWER Directive 9200.4-17P, the site-specific data evaluation was organized into multiple lines of evidence. Table 4-1 summarizes the data assembled to evaluate the MNA remedy for the Site. It also cross references the various sections of this technical memorandum where data evaluation details are provided. Table 4-1 shows that there are five

existing lines of evidence across all three data tiers (as defined by the OSWER Directive 9200.4-17P), all of which provide evidence for the effectiveness of the site-specific NA mechanisms.

Also included on Table 4-1 is a column which provides an additional cross reference to data collected by the North Cavalcade Superfund Site remediation team. North Cavalcade underwent a similar evaluation of NA processes and came to similar conclusions. Details of the work and results at the North Cavalcade Site can be found in various documents (CH2M-HILL, July 2010, CH2M-HILL, January 2008, and USEPA, July 2009).

**Table 4-1**  
**Lines of Evidence Supporting Monitored Natural Attenuation Remedy**  
**South Cavalcade Superfund Site**  
**Houston, Texas**

Tier	Line of Evidence	Observed Behavior	TM Section Reference	Indicative of Effective NA?	Affirmed by Data for N. Cavalcade?
1	Stable groundwater concentrations in sentinel downgradient wells	Leading edges of the plumes appear stable as shown by stable or decreasing COI concentrations in downgradient wells; Downgradient plume extents defined by samples showing concentrations below detection limits.	4.1	Yes	Yes
1	Analytical modeling indicates that biodegradation is controlling plume migration	Actual plume length is significantly shorter than would occur if biodegradation were not occurring; Concentrations downgradient are similar to those predicted with consideration of biodegradation.	4.5	Yes	Yes
2	Geochemical footprint indicates that conditions are more reduced in the core of the plume than on the exterior	Consumption of sulfate electron acceptor downgradient (as compared to upgradient or side gradient) and production of ferrous iron and manganese are indicative of microbiological activity.	4.2	Yes	Yes (iron, sulfate, methane and carbon dioxide)
2	Geochemical reaction stoichiometry used to estimate the quantity of hydrocarbon degradation that can be supported by the observed geochemical conditions	Mass budgeting analysis indicates that the assimilative capacity of NA at the North Area is up to approximately 23 mg/L up to 37 mg/L in the South Area; NA is roughly capable of sustaining degradation of up to 59 pounds per year of hydrocarbon mass in the North Area and 46 pounds per year in the South Area.	4.3	Yes	Yes
3	PLFA analysis to document the viability of the microorganisms within the contaminant plume	Biomass in solid samples (1999) was more than an order of magnitude higher in the contaminant plume than outside. There is a larger fraction of the microbial population as Proteobacteria (Monos) and Anaerobic metal reducers (BrMonos) within the plume. Physiological status of the microbes in the plume exhibit a small response to the presence of contaminants.	4.4	Yes	Yes

Notes:

1. Line of Evidence Tiers defined as per OSWER 9200.4-17P (EPA, April 1999).

## 4.1 Contaminant Distribution and Trend Analysis

Trends in dissolved phase COI distributions are the primary line of NA evidence because they can provide a direct indication of whether the plume is advancing or showing signs of behavior that is consistent with NA. The data for indicator COI trends in representative downgradient wells are summarized in Table 4-2, and consist of results for the Shallow Zone in the South Area, the Shallow Zone in the North Area, and the Interbedded Zone Site-Wide (KEY, 2008). Naphthalene and benzene are used as overall indicator parameters for the COIs, given that they are the most extensively distributed constituents in groundwater at creosote sites in general, and at the South Cavalcade Site in particular.

Table 4-2 provides a parsed summary of the historic data focusing on monitoring wells located downgradient of source areas. As is shown in Table 4-2, concentrations have decreased or remained stable downgradient of the source area. The only well at the Site that has exhibited an increase in concentration is a source area well (OW-10). This well showed an increase in benzene concentrations that is not representative of actual groundwater chemistry as a result of the known presence of DNAPL at this location. The apparent increase in dissolved benzene concentration at OW-10 is likely due to entrainment of variable amounts of DNAPL in the groundwater samples, and is not representative of actual groundwater chemistry.

**Table 4-2**  
**Historical Benzene and Naphthalene Concentrations in Monitoring Wells Downgradient of Source Areas**  
**South Cavalcade Superfund Site**  
**Houston, Texas**

Houston, Texas		Concentration (ug/L)							Trend <sup>(1)</sup> (Basis)
Well	Site Constituent	Dec-86	Feb-87	Nov-93	Dec-99	Apr-00	Jul-00	Sep-05	
Shallow Zone - North Area									
MW-01	Benzene	2 J	15	5.7	-	4.1	-	13 U	ST (MK)
	Naphthalene <sup>(2)</sup>	3100	3400	1600	-	340	-	2100	ST (MK)
MW-25	Benzene	-	-	-	-	2.6	0.13 U	0.13 U	NC (QE)
	Naphthalene	-	-	-	-	0.36 U	0.26 U	0.26 U	NC (QE)
Shallow Zone - South Area									
MW-04	Benzene	50 J	-	12	-	-	-	-	DC (QE)
	Naphthalene	540	280	460	-	-	-	-	ST (QE)
MW-08	Benzene	5 U	-	-	1 U	-	-	-	NC (QE)
	Naphthalene	24	2 J	-	7.3 J	-	-	-	ST (QE)
MW-26	Benzene	-	-	-	-	0.1 U	-	13 U	NC (QE)
	Naphthalene	-	-	-	-	4300 D	-	1700	DC (QE)
Interbedded Zone									
P-01	Benzene	5 U	-	-	-	-	-	0.13 U	NC (QE)
	Naphthalene	10 U	20 U	-	-	-	-	0.26 U	NC (QE)
P-05	Benzene	5 U	-	-	-	-	-	3.1	ND (QE)
	Naphthalene	2400	20 U	-	-	-	-	320	DC (QE)
P-03R	Benzene	800	-	-	-	2.9	-	1.3 U	DC (QE)
	Naphthalene	14000 0	15000	-	-	0.36 U	-	230	DC (MK)

1. Trend abbreviations are as follows:

ST – Stable conditions.  
NC – Negligible concentrations (at or below detection limit).  
DC – Declining concentrations.

Basis abbreviations are as follows:

MK – Mann-Kendall Test for Trend  
QE – Qualitative Evaluation.

2. Prior to 2005, naphthalene analyzed via SW-846 Method 8270. 2005 naphthalene concentrations based on SW-846 Method 8260. SW-846 Method 8270C will be used for naphthalene analysis going forward.

As shown in Table 4-2, there are multiple sampling events available for these wells, in the period between December 1986 and September 2005. The results for the downgradient wells are clearly indicative of stable conditions. Concentrations are consistent or declining over time. A statistical assessment of trend was completed for the results of each of the wells summarized in Table 4-2, as well as for numerous other wells located at the Site. Where four or more data points were available, the trend was quantitatively evaluated using the Mann-Kendall test for trend. A qualitative assessment was made if fewer than four measurements were available for a given well).

A discussion of the assessment and the results of the trend analysis are summarized in the Focused Feasibility Study (FFS) Report (KEY, 2011). Trend analyses for benzene and naphthalene concentrations for a total of 38 wells located across the Site in both the Shallow and Interbedded Zones were summarized in the FFS.

These trends are also shown graphically, in two different formats. Figures 4-1 and 4-2 present both historical and current iso-concentration contours for dissolved naphthalene in the Shallow Zone. Similarly, Figures 4-3 and 4-4 present historical and recent iso-concentration contours for dissolved benzene in the Shallow Zone. These figures generally show trends of lower concentrations and reduced plume sizes over time for both areas and both constituents. Also presented to support the conclusion of reduced plume concentrations are time series plots (Figures 4-5A through H) for several wells that were sampled more than once (KEY, 2008).

Indicator COI concentration trends are consistent with NA. Over a 22 year period, indicator COI concentrations remained stable or decreased at 37 of 38 (over 97%) of the monitoring well locations which have been sampled and analyzed for benzene and naphthalene. Complete historical results for naphthalene and benzene are summarized in the FFS. Overall, these data indicate that the dissolved phase distributions are consistent with NA throughout the Site, in both the Shallow and Interbedded Zones.

## **4.2 Geochemical Footprint Analysis**

Although the mechanisms that destroy contaminants in groundwater cannot be observed directly, they leave "footprints." Footprints occur because the mechanism controlling contaminant fate also consume or produce other chemical compounds, some of which can be measured in groundwater. Thus, an observation of the loss of contaminant, coupled with observation of several associated footprints, helps to establish the cause and effect to document NA.

The intent of the geochemical footprint analysis is to geospatially evaluate the distribution of several key groundwater parameters that are indicative of biological footprints at the Site. Key geochemical indicators of contaminant biodegradation processes include the following observations within the PDSAs and contaminant plume:

- Reduced dissolved oxygen concentration (DO)
- Reduced oxidation reduction potential (ORP)
- Reduced nitrate concentrations
- Increased ferrous iron concentrations
- Reduced sulfate concentrations

- Increased methane concentrations
- Increased dissolved inorganic carbon (CO<sub>2</sub>) concentrations
- Increased alkalinity

The site-specific geochemical footprints are illustrated in Figure 4-5 and Figure 4-6 (ORP, sulfate, nitrate, methane, ferrous iron and manganese in aquifer zones) for the North and South Areas, respectively. These figures illustrate the boundary between aerobic and anaerobic conditions based on potential TEAPs: DO, ferrous iron, sulfate, and methane.

In the North Area, ORP measurements ranged from -153 to +134. In the South Area, the range is from -126 to +105. The highest ORPs (generally indicating oxidizing conditions) are found in either the cross-gradient of the source area or several hundred feet downgradient. ORP results greater than zero were found in samples from monitoring wells upgradient (MW-07, MW-03), cross-gradient (OW-7) and downgradient (MW-25 and MW-26) of the plume. The lowest ORP results (indicating strongly reducing conditions) are found closest to the source areas, likely a result of intense electron acceptor utilization and biodegradation. This effect is most pronounced in the North Area, and somewhat less pronounced in the South Area.

Iron and manganese are utilized in biodegradation reactions; they convert from oxidized forms on the aquifer solids to reduced forms which dissolve in groundwater. Consequently, if these metals play a significant role in biodegradation, their dissolved phase concentrations should be elevated in the vicinity of the source zone, and lower in background groundwater. This trend is strongly apparent for both metals in the vicinity of the estimated Northern Area source zone and somewhat apparent in the estimated Southern Area source zone. For example, the highest dissolved iron and manganese concentrations in the North Area are found in well DPN-L2 (22 and 9.1 mg/L, respectively), which is adjacent to the source area, and the lowest concentrations (below 1 mg/L) either cross-gradient or about 500 feet downgradient of the source.

According to the expected progression of electron acceptor utilization, nitrate should be elevated in background groundwater and depleted near the source. The observed trend for this parameter, however, is somewhat inconclusive, probably as a result of nitrate depletion or scarcity in background groundwater upgradient of the Site. The distribution of nitrate in the Northern Area (Figure 4-1) conforms somewhat to expected conditions, but the trend is not strong.

Sulfate is depleted to non-detectable levels within the estimated source zones, and is generally present at concentrations in excess of 50 mg/L in background groundwater samples. This trend is consistent with utilization of sulfate as an electron acceptor in biodegradation reactions. From a mass balance perspective, sulfate appears to be one of the most important electron acceptors for COI biodegradation at the Site. The Site's sulfate concentration trend is very strong and is typical of a trend that has been observed at other wood treating or coal tar sites, including North Cavalcade.

Methane concentrations are expected to increase in the vicinity of the source zone, due to the activity of methanogenic microbes in the most reduced area of the Site. Methane is expected to decrease downgradient of the source as methane itself is consumed through biodegradation reactions. Again, as in the case of nitrate, the observed trend is not strong. Some evidence of

methane production in the Northern Area source zone is apparent. In general, however, methane concentrations remain relatively low across the Site, possibly indicating that the supply of other electron acceptors (e.g., sulfate) is sufficient to prevent the source zone from becoming reduced to the degree required to support methanogenesis.

The above evaluation of potential TEAPs suggests that a range of oxidation-reduction conditions exist across the Site within the contaminant plume. The contaminants appear to be stimulating more active biodegradation within these areas, with strong evidence for utilization of electron acceptors. The following mass budgeting and assimilative capacity analysis seeks to quantify the biodegradation that is associated with each electron acceptor.

#### **4.3 Mass Budgeting and Assimilative Capacity Analysis**

Quantification of the natural in-situ biodegradation that is occurring at the Site was evaluated by more closely examining the groundwater chemistry in the shallow sand. The Interbedded Zone was not considered in the South Cavalcade assessment given the discontinuous nature of this unit as well as the small quantity of DNAPL mass present in the Interbedded Zone versus the Shallow Zone. However, given the similarity in geology between the North Cavalcade and South Cavalcade Sites, it is possible to use the mass budgeting estimates derived for the Interbedded Zone for the North Cavalcade Site to represent the assimilative capacity of this unit at the South Cavalcade Site.

The method employed is based on that described in "Natural Attenuation for Groundwater Remediation" (NRC, 2000). The method examines the changes in groundwater chemistry that are observed across the Site from upgradient to downgradient of the contamination. Parameters evaluated include DO, methane, ferrous iron, nitrate, sulfate, and contaminant concentrations (Attachment 2). Analytical data for samples from wells in the North and South Areas (upgradient, source area, and downgradient wells) were used to predict best case, average, and worst case biodegradation. The effort assumed that all changes in the parameters are caused by biodegradation of the bulk contaminants at the Site (expressed in terms of toluene equivalents).

The amount of contaminant degraded is estimated from the stoichiometric relationships between the contaminant and each parameter. The NA assimilative capacity and degradation rates in pounds per year are estimated and reported. Attachment 3 presents the calculations performed for the mass budgeting and assimilative capacity analysis.

As shown in Table 4-3, the assimilative capacity of the Shallow Zone in the Northern Area averages 16.2 mg/L and that of the Shallow Zone in the Southern Area is estimated to average 25.3 mg/L. Because of the similarities in the geology of the Interbedded Zone at the North Cavalcade Site and the South Cavalcade Site, the assimilative capacity in the Interbedded Zone for the South Cavalcade Site is estimated to average 10 mg/L. In both groundwater zones, sulfate reduction accounts for all or most of the total assimilative capacity with iron reduction, aerobic respiration and methanogenesis making up the majority of the balance.

**Table 4-3**  
**Mass Budgeting Analysis**  
**South Cavalcade Site**  
**Houston, Texas**

Reaction <sup>(1)</sup>	Acceptor Concentration Observed Change (mg/L)	Computed Change Total CO <sub>2</sub> (mg/L)	COI Assimilative Capacity (mg/L)	COI Biodegradation Rate (lbs COIs/yr)
<b>Shallow Zone - North Area (Average Values)</b>				
Aerobic Respiration (O <sub>2</sub> )	0.100	0.029	0.032	
Denitrification (NO <sub>3</sub> <sup>-</sup> as N)	0.000	0.000	0.000	
Sulfate Reduction (SO <sub>4</sub> <sup>2-</sup> as S)	22.75	12.058	14.492	
Iron Reduction (Fe <sup>2+</sup> generated)	3.887	0.163	0.179	
Methanogenesis (CH <sub>4</sub> generated)	1.203	0.505	1.540	
<b>Total</b>		<b>12.7</b>	<b>16.2</b>	<b>40.7</b>
<b>Shallow Zone - South Area (Average Values)</b>				
Aerobic Respiration (O <sub>2</sub> )	2.600	0.754	0.829	
Denitrification (NO <sub>3</sub> <sup>-</sup> as N)	0.005	0.004	0.005	
Sulfate Reduction (SO <sub>4</sub> <sup>2-</sup> as S)	40.75	21.598	25.958	
Iron Reduction (Fe <sup>2+</sup> generated)	0.700	0.029	0.032	
Methanogenesis (CH <sub>4</sub> generated)	0.073	0.030	0.093	
<b>Total</b>		<b>20.9</b>	<b>25.3</b>	<b>31.5</b>
<b>Interbedded Zone (Average Values)<sup>(2)</sup></b>				
Aerobic Respiration (O <sub>2</sub> )	3.5	1	1.100	
Denitrification (NO <sub>3</sub> <sup>-</sup> as N)	0	0	0.000	
Sulfate Reduction (SO <sub>4</sub> <sup>2-</sup> as S)	13	7	8.400	
Iron Reduction (Fe <sup>2+</sup> generated)	0.7	0.03	0.030	
Methanogenesis (CH <sub>4</sub> generated)	0.61	0.25	0.780	
<b>Total</b>		<b>8.3</b>	<b>10.000</b>	<b>64</b>

**Notes:**

- Reactions considered to compute change in indicator COI (Benzene and Naphthalene), and Inorganic Carbon (as CO<sub>2</sub>). See Attachment 3.
- Values for North Cavalcade Site used. See Table 4-3 (CH2MHill, July 2010). Conditions in this formation assumed similar to N. Cavalcade.

After applying groundwater hydraulics of continuous electron acceptor supply to the assimilative capacity, the predicted biodegradation rates average 40.7 pounds per year (lbs/yr) and 31.5 lbs/yr for the Shallow Zone in the Northern Area and Southern Area, respectively. Based on the work performed for the Interbedded Zone at North Cavalcade, biodegradation rates are estimated to average of 64 lbs/yr (CH2M-HILL, July 2010).

#### 4.4 Microbiological Evidence

Phospholipid fatty acid (PLFA) analysis was conducted on seven soil samples collected from the Shallow Zone (Attachment 4) in November 2000. Three locations were re-sampled in January 2003. PLFAs comprise a main part of bacteria cell membrane. PLFA analysis provides a tool for assessing the number and type of viable (live) bacteria present in an aquifer and their community structure. The Interbedded Zone was not included in the work performed for South Cavalcade. However, although thicknesses and depths are slightly different for the Interbedded Zone at the two Sites, the geology and geochemistry is similar and the results for the North Cavalcade Site are therefore considered representative of the South Cavalcade Site as well.



The PLFA analyses are consistent with the other geochemical data that indicate that the viable bacterial populations have an elevated level of bioactivity within the impacted aquifer and indicate that biodegradation of Site contaminants is occurring. Overall, the PLFA analyses indicate unique, low-diversity, and only slightly stressed populations of bacteria outside of the contaminant plume. The bacteria populations are similar at sampling locations within the impacted groundwater plume and the population diversity is high and typical of environmental samples collected from more anaerobic conditions. The analytical results for the PLFA study are summarized in Table 4-4.

**Table 4-4**  
**PLFA Sampling and Analysis Results - January 2000**  
**South Cavalcade Superfund Site**  
**Houston, Texas**

Sample ID	Location	Sample Date	Cells per gram	Gram Positive	Gram Negative	Branched Monoenoics	Mid-Chain Branched Saturated	Normal Saturated	Eukaryotes
DPN-L1	North Area Source Area	12/07/99	3.09E+06	13.8	40.4	2.9	16.6	18.1	8.2
DPN-L2	North Area Source Area	12/07/99	2.78E+06	12.2	36.2	2.5	15.4	19.4	14.4
MW-03	North Area Upgradient	12/07/99	1.22E+07	15.6	25.5	2.5	34.7	17.6	4.1
OW-07	North Area Side Gradient	12/07/99	1.63E+06	14.8	15.9	1.2	44.4	16.5	7.2
MW-07	South Area Upgradient	12/07/99	2.34E+07	17.9	31.5	4.1	22.7	18.3	5.5
DPS-L1	South Area Source Area	12/08/99	6.45E+06	13.7	30.7	4.4	16.6	20.6	14.0
DPS-T0	South Area Source Area	12/08/99	2.33E+07	14.9	31.8	2.9	24.7	15.3	10.4

### Biomass

The estimated viable biomass ranged from  $10^6$  to  $10^7$  cells/gram. The samples exhibiting higher biomass were collected from borings within or near the source areas (the upgradient wells were located very close to the source areas). The sample with the lowest biomass (i.e., the sample from OW-07) was collected outside of the impacted northern area. This sample was obtained to act as a control sample. Biomass populations in samples collected near the source areas were up to an order of magnitude greater than those in samples obtained from the well located side-gradient to the plume.

### Community Structure

The control sample (OW-07) contained a different population structure from the remaining samples. The sample from OW-07 contained predominantly *Actinomyces*, while the samples collected from within the plume or source areas contained 25 to 40 % gram negative (monoenoic) PLFA. Monoenoic PLFA consist of fast-growing bacteria that utilize many carbon sources and adapt quickly to a variety of environments.

Other major groups of PLFA in the plume/source samples included primarily normal saturated PLFA (found in both prokaryotes and eukaryotes), terminally-branched saturated PLFA (representative of gram positive bacteria) and Mid-chain branched saturates (common in sulfate

reducing bacteria and certain gram positive bacteria). These types comprised roughly 12 to 34 percent each, of the seven samples.

The community structure indicated that population diversity is high in a majority of the samples. Proteobacteria were the predominant bacterial type in most samples. Proteobacteria often grow opportunistically, due to their ability to use a variety of carbon sources and to adapt quickly to environmental conditions.

At the North Cavalcade Site, the majority of samples from within the impacted groundwater plume contained similar PLFA profiles, of approximately 45-70% monoenoic PLFA (indicative of proteobacteria), 5-20% terminally branched PLFA (indicative of Firmicutes), and minor proportions of other types of PLFA. High proportions of terminally branched PLFA (> 15 % ) are often seen in environmental samples collected from more anaerobic conditions (CH2M-HILL, 2010). Samples from several locations at North Cavalcade had unique community structures:

- MW-07, within the contaminant plume, contained ~66 % eukaryotic (polyenoic PLFA) and also one of the highest levels of biomass.
- CAV-OW-07, outside the contaminant plume, had only monoenoic and normal saturated PLFA.
- OW-09 and OW-08, located outside the contaminant plume, and OW-11, located within the contaminant plume, had primarily normal saturated PLFA. These samples also had some of the lowest biomass.

Because normal saturates are present in all living organisms, their presence does not provide much information about the community structure, however, high proportions of normal saturates are generally associated with simple microbial communities.

### **Physiological Status Biomarkers**

Physiological status biomarkers for starvation and for microbial response to environmentally induced stress showed that most of the samples were experiencing only a low level of starvation, and no stress response of note. Most of the samples were shown to be in the stationary phase of growth. The samples from MW-03, MW-07, and DPN-L1 had the fastest turnover rates.

In addition, several samples from South Cavalcade exhibited monoenoic markers that are indicative of communities under stress, showing decreased membrane permeability in response to changes in their environment (i.e., the presence of hydrocarbons).

Similarly, for the North Cavalcade Site Interbedded Zone, PLFA samples indicated a higher stress response and moderate starvation in the source area, and high levels of starvation (i.e. slowest bacterial growth) were seen in samples from outside the impacted groundwater plume, such as OW-08 (CH2M-HILL, 2010).

## 4.5 Fate and Transport Modeling Results

Fate and transport modeling was conducted by Key Environmental, Inc., for the most mobile constituents of interest (BTEX and PAHs) for the North and South Areas. Of the COIs modeled, benzene and naphthalene are considered to be the most mobile. The fate and transport evaluations were conducted using protective assumptions regarding constituent fate and transport and potential future use of shallow groundwater to ensure that the potential for future exposure to groundwater constituents is not underestimated. Conservative, yet realistic input values for the COIs were used (KEY, 1997; KEY and Groundwater Insight, 2000)

### Shallow Zone

An initial "worst case" evaluation of the fate and transport of dissolved constituents in groundwater was performed through the use of a one-dimensional analytical model that simulates the dispersion of constituents in groundwater and subsequent attenuation, via adsorption to organic matter within the aquifer matrix, as a function of groundwater velocity, time, and distance from the potential constituent source. This assessment was completed using a modified form of the Ogata-Banks equation, which is a one-dimensional solution to the dispersion-advection equation. A one-dimensional solution was considered to be appropriate for the initial simulations to satisfy the objective of providing a "worst case" and most protective estimation of potential constituent transport. The Ogata-Banks equation was selected for these simulations because it is a referenced and peer-reviewed analytical solution and it is capable of simulating the fate and transport of dissolved constituents originating from a continuous source (i.e., non-aqueous phase liquid). A Microsoft Excel™ spreadsheet program was developed for conducting the Ogata-Banks simulations.

The Ogata-Banks equation assumes that a continuous source of dissolved phase constituents exists at a specific location ( $x$ ) and that the concentrations of dissolved constituents at the downgradient limit of the source area (i.e.,  $x=0$ ) remains constant over time at the effective solubility of the COI. Free-phase and residual DNAPL have been observed in the shallow aquifer in the southwest area of the Site (the former wood treating process area), southeast area (the former coal tar plant area) and in a small area in the northern portion of the Site (in the vicinity of DNAPL recovery well RWN-4). The rate of dissolution of the DNAPL into the shallow groundwater is limited by the relatively low effective solubilities of the DNAPL constituents and, to a lesser extent, by the relatively low groundwater flow velocities.

Therefore, it is reasonable to assume for the purpose of the proposed simulations, that the free phase and/or residual DNAPL act as a continuous source for dissolved phase constituents. Based on this assumption, the Ogata-Banks equation is a valid analytical model for simulation of the fate and transport of dissolved constituents in groundwater over time.

Additional simulations that considered the potential effects of intrinsic biodegradation were then performed. The analytical simulations considering the effects of intrinsic biodegradation were performed using the BIOSCREEN computer software program obtained through the EPA Center for Subsurface Modeling Support in Ada, Oklahoma. The BIOSCREEN model was selected for these simulations because this analytical model is predicated on the same boundary conditions and assumptions as the Ogata-Banks equation. The BIOSCREEN computer tool is capable of

simulating intrinsic biodegradation as a first order kinetic reaction (i.e., decay process). Similar to the modified Ogata-Banks equation, this simulation incorporates the effects of advection, dispersion, and adsorption (KEY, 1997; KEY and Groundwater Insight, 2000).

This simulation is based on the Domenico (1987) "analytical model for multi-dimensional transport of a decaying contaminant species." The BIOSCREEN simulation can be considered to be the multi-dimensional analogue to the modified Ogata-Banks equation with the additional consideration of first order decay of the contaminant species. By assigning an infinite value to the half-life for the constituent source decay, this solution can be used to simulate the fate and transport of dissolved phase constituents from a DNAPL source. Therefore, the BIOSCREEN solution was determined to be appropriate for use in this fate and transport evaluation.

The significant conclusions of the fate and transport evaluation for the South Cavalcade Site are summarized below:

- Incorporation of biodegradation effects into the analytical model simulations is justified by the demonstration and documentation of intrinsic biodegradation of dissolved creosote constituents in groundwater at several similar sites. Additionally, the reduced concentrations of an electron acceptor (sulfate) and the relatively stable observed constituent concentrations over time also support incorporation of biodegradation effects into the fate and transport evaluation. Also, the benzene concentrations predicted by the Ogata-Banks analytical simulations using the best case input transport parameter values are significantly greater than the actual benzene concentrations determined through laboratory analysis of groundwater samples. Thus, the reduced concentrations of benzene observed at the Site downgradient of the constituent source areas, as demonstrated by previous laboratory analyses of groundwater samples, cannot be solely attributable to adsorption and dispersion processes alone. These findings indicate that other processes, such as biodegradation, are in fact acting to retard the migration or naturally attenuate COIs in the shallow aquifer.
- The results of the worst case BIOSCREEN simulations demonstrate effective NA of COIs within a short distance of potential constituent source areas and well before groundwater concentrations greater than the ROD remedial goals or the applicable Texas Groundwater Quality Standards<sup>1</sup> are realized at the nearest hypothetical future groundwater withdrawal well.
- The results of the BIOSCREEN simulations using protectively assumed constituent half-life values indicate that the COIs in the shallow groundwater have already achieved a steady state or equilibrium distribution. These simulations indicate that

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<sup>1</sup> At the time the modeling was completed, the applicable Texas Groundwater Quality Standards (i.e., ARAR) were the Texas Risk Reduction Standard (30TAC Chapter 335) Medium Specific Concentrations for Groundwater. Currently, the applicable Texas Groundwater Quality Standards (i.e., ARAR) are the Texas Risk Reduction Program (30TAC Chapter 350) Protective Concentration Levels.

future migration or increasing concentrations of COIs will not occur. The simulations were completed using the transport input parameter values and degradation rates which favor the prediction of greater migration distances and constituent concentrations. Thus, these simulations are considered to represent a protective prediction of the steady state distribution of dissolved COIs in groundwater. This conclusion is supported by a comparison of the 1986-87 groundwater concentration data with data obtained from the supplemental groundwater sampling completed in November 1993. Comparison of these data indicates stable or decreasing constituent concentrations between 1986-87 and 1993.

- The results of the worst case fate and transport simulations under non-pumping conditions predicted concentrations of the more mobile and biodegradable COIs several orders of magnitude greater than the actual concentrations determined through previous groundwater analysis. Despite the use of transport parameter values in this simulation which favor the prediction of greater migration distances and constituent concentrations, several of the higher molecular weight PAH compounds were demonstrated to be immobile and sufficiently attenuated by this overly protective evaluation. The results of the fate and transport evaluations indicate that implementation of a NA remedy at the South Cavalcade Site is feasible.

#### Interbedded Zone

Because the modeling effort for South Cavalcade focused on the Shallow Zone, information from the North Cavalcade modeling effort on the Interbedded Zone is presented in this section. Given the similarity in geology of the Interbedded Zone between North and South Cavalcade, the results achieved by CH2M-HILL (2010) are appropriate to evaluate NA in the Interbedded Zone at South Cavalcade.

A site-specific steady-state numerical fate and transport model (MODFLOW jMT3DMS) was developed for North Cavalcade in 2006 for the following purposes:

- Develop a conceptual flow model of groundwater flow and contaminant transport from review of Site characterization data.
- Create a numerical flow model incorporating lithology, hydrology and boundary conditions based on the conceptual model
- Calibrate the flow model to head data by adjustment of hydraulic conductivity values with low residual tolerance
- Create a numerical transport model to use the flow model results. Estimate contaminant source parameters (size, strength), and transport parameters (porosity, sorption, chemical data, etc.) from existing Site characterization data.

- Calibrate the transport model to existing naphthalene and benzene concentration data in 2005 by adjustment of source strength, degradation rates, and dispersion coefficients.
- Conduct predictive transport simulations and estimate contaminant concentrations after 100 years under a source stabilization scenario. (MNA as a supporting remedy to treat dissolved contamination outside of the stabilization zone).

The transport model, focused on the Interbedded Zone, was able to reasonably reproduce the 2004 naphthalene and benzene plumes and suggest that biodegradation is likely a significant control on the present distribution of both contaminants.

Table 4-5 presents a summary of the key data used to represent the Shallow and Interbedded Zones at North and South Cavalcade Sites. Naphthalene and benzene were used because they are considered to have the highest risk potential based on their mobility, toxicity and prevalence at the two Sites. In all cases, conservative input values were used to ensure that the models did not understate potential migration beyond the property lines.

**Table 4-5**  
**Summary of Fate and Transport Model Input Parameters**  
**South Cavalcade Superfund Site**  
**Houston, Texas**

Parameter	Shallow Zone		Interbedded Zone Site-Wide <sup>(1)</sup>
	North Area	South Area	
Source Age	1962	1962	1955
Fractional Organic Carbon	0.00086	0.00086	0.000122
Effective Porosity	0.375	0.375	0.4
Naphthalene Half Life	258 days	258 days	25 years
Benzene Half Life	2 years	2 years	4 years
Naphthalene Retardation Coefficient	4.9	4.9	1.5
Benzene Retardation Coefficient	1.2	1.2	1
Naphthalene Solubility and Untreated Source Concentration	12.73 mg/L	12.73 mg/L	17 mg/L
Benzene Solubility and Untreated Source Concentration	3.799 mg/L	3.799 mg/L	0.4 mg/L
Hydraulic Conductivity	1.6 ft/day	0.11 ft/day	Variable - average 12 to 20 ft/day
Average Saturated Thickness	15	15	5.8 feet
Post-Stabilization Hydraulic Conductivity	NA	NA	0.01 ft/day
Post-Stabilization Benzene Source Concentration	NA	NA	0.005 mg/L
Post-Stabilization Naphthalene Source Concentration	NA	NA	0.15 mg/L

Notes:

1. Interbedded zone input parameters are for the North Cavalcade Site.

The most significant basis for concluding that biodegradation is controlling plume migration is the relatively small observed plume length in comparison to those simulated without biodegradation. Simulations suggest that the benzene and naphthalene plumes are stable.

For the North Area, under the most conservative scenario (no pumping, no biodegradation), the predicted downgradient exposure concentration of benzene was 3,800 ug/L which would have arrived at a point 425 feet downgradient within one-half year of the source creation. In reality, the measured concentration of benzene in a well 260 feet downgradient of the source was only 6 ug/L. When minimal biodegradation was considered in the BIOSCREEN model, the predicted



concentration in this sentinel well (3,190 ug/L) was 500 times greater than the measured concentration.

Similarly, for naphthalene in the North Area, the transport model indicated a worst-case arrival time at the hypothetical exposure point 425 feet downgradient of 2.5 years at a concentration of 12,700 ug/L. The measured concentration in the downgradient well 260 feet from the source area was only 1,600 ug/L. When half life was considered in the BIOSCREEN model, the measured concentration (1,600 ug/L) was similar to the predicted concentration of 2,043 ug/L.

In the South Area, the most conservative model indicated that the concentration at the hypothetical exposure point (400 feet downgradient) would reach 3,800 ug/L within only 5 years. In reality, no benzene was detected in a well 350 feet downgradient. When biodegradation was considered, the predicted concentration in this monitoring well was 40 times greater than the method detection limit, which was used as a surrogate given that benzene was not detected (207 ug/L vs. 5 ug/L). When median values of hydraulic conductivity, half life, and other input parameters were used, the results still predicted concentrations an order of magnitude higher than the observed concentrations.

The most conservative scenario also resulted in a predicted downgradient concentration of naphthalene of 12,700 ug/L within 35 years. However, the maximum detected concentration of naphthalene in this sentinel well was 24 ug/L. Because even this conservatively estimated concentration is well below the potentially applicable criteria for naphthalene, no additional modeling was conducted.

### **Uncertainty**

Prominent uncertainties in the transport model include unknown source dimensions and the true effective solubility of the constituents under site-specific conditions. The model does not exactly match the observed plume conditions where contaminant concentrations are observed to decrease dramatically in a very small distance. As shown on Figures 4-2, at the edge of the naphthalene plumes, concentrations drop from 1,700 and 3,900 ug/L in the North and South Areas, respectively, to non-detect in a very short distance. The simulation predicts higher concentrations than have been observed. It is important to note that the plume conditions did not change between the time the modeling was completed (1997) and the time that the most recent comprehensive monitoring event was completed (2005), indicating that the model is most likely overly conservative. There are several possible explanations for this observation:

- As discussed in Section 2, the conductive Shallow Zone sediments are highly variable, but typically contain more clay, or even pinch out to the west (downgradient). In addition, the Interbedded Zone also thins to the west. Thus natural lithologic barriers may be acting to limit contaminant migration.
- As discussed in Section 4.3, the redox state of the groundwater transitions to more oxic conditions at the plume toes and NA mechanisms may be effective at controlling plume migration.



- The true effective solubilities of the constituents of interest may be significantly lower than those used for the simulation purposes. For example, although an effective solubility of benzene of approximately 3,800 ug/L was used, the highest concentration ever encountered in samples obtained near a PDSA was less than 1,000 ug/L.

Regardless of the explanation, the fate and transport modeling results generally support the geochemical and contaminant monitoring data that demonstrate that the benzene and naphthalene plumes are undergoing active biodegradation.

## **5.0 Summary of Efficacy of NA**

NA is believed to be an acceptable remedy for dissolved contamination at the South Cavalcade Site for the following reasons:

- Multiple lines of evidence discussed above suggest that NA is actively controlling the benzene and naphthalene plumes and actively reducing toxicity, mobility, and volume (TMV) through biodegradation of the contaminants to innocuous byproducts.
- Site geology is favorable for NA. A massive clay layer exists beneath the Site and the fining westward (downgradient) and pinching out of the Interbedded Zone is a natural impediment to plume growth.
- There is no current or projected future risk of impacted groundwater exposure to human health or ecological receptors. While the groundwater within the shallow sand and Interbedded Zone might satisfy potentially applicable water quality criteria, it is highly unlikely that this water resource will be needed for drinking water purposes in the foreseeable future because of the proximity of a public potable water service. A major highway is planned for the area to the west of the Site which will serve to eliminate access to groundwater in this area.
- The effectiveness of a NA remedy is competitive with the other remedial alternatives described in the FFS (KEY, 2011). Contaminant mass removal by available remedial technologies is technically impracticable. The residual DNAPL will constitute a dissolved phase source for decades regardless of the technology employed.

## **5.1 NA Restoration Timeframe**

The site-specific fate and transport model (see Section 4.5) was used to estimate the timeframe for NA to achieve the remediation goals for naphthalene in the shallow groundwater, including that in the DNAPL source areas. The input parameters used for the modeling effort were summarized in Table 4-5.

The target concentration for naphthalene was defined as 1.46 mg/L for the South Cavalcade modeling effort. The initial effort included as estimation of the time required to deplete the naphthalene in the source area. This was estimated to exceed 170 years. Upon depletion of the source zone, degradation was evaluated for the time needed to reduce groundwater concentrations to acceptable levels (i.e., the target concentration). The modeling results indicated that the total time for naphthalene to attain remediation standards (after source

stabilization) via natural attenuation is estimated to be 173 years or more (KEY, 2008). Other more soluble constituents (e.g., benzene) could conceivably attain standards in a shorter time frame, although the standards for compounds such as benzene are lower than that for naphthalene which may offset the decrease in attainment time attributable to solubility. Less soluble constituents are not of concern for the groundwater given sorption of such constituents.

MNA is being considered as a remedial alternative to maintain attainment of remedial goals for groundwater outside of the proposed TI Waiver Zones. A long-term groundwater monitoring program will be developed and implemented to verify ongoing groundwater restoration outside of the proposed TI Waiver Zone.

## **5.2 Uncertainty**

This evaluation documents the efficacy of NA processes to reduce benzene and naphthalene TMV and contains adequate support to select it as a dissolved phase contaminant remedy component. The major uncertainty associated with the South Cavalcade Site results from the use of literature values for the half life of benzene and naphthalene in groundwater. This is considered most important for naphthalene which has historically been detected at the highest concentrations in groundwater samples obtained at the Site.

The naphthalene degradation simulations completed for the South Cavalcade agree well with the analytical results obtained for samples from downgradient monitoring wells and, in fact, the simulations predict higher concentrations than have been observed. Furthermore, the half-life used for the South Cavalcade Site is consistent with the half-lives (or calculated half-lives based on rate constants) reported in the literature, including the literature sources cited in the North Cavalcade NA Technical Memorandum.

Nonetheless, there is significant variability in the literature half-life data for naphthalene presented herein has some inherent uncertainty. However, it is considered unlikely that the degradation rates are overestimated based on the conservative analytical modeling performed as part of the GFTER. However, in view of the uncertainty associated with the degradation rates, it is considered appropriate that monitoring be continued as is discussed in the following section.

## **6.0 Path Forward**

Moving forward, the next steps to take for implementation of the NA alternative are to finalize the FFS, the Human Health Risk Assessment, and the Technical Impracticability demonstration. Upon completion of these activities an amendment to the ROD incorporating MNA as the preferred remedial alternative will be prepared. In consideration of the multiple lines of evidence that have been developed for the South Cavalcade Site and the conclusion that Monitored Natural Attenuation is feasible for both Shallow and Interbedded zone groundwater, it is recommended that an appropriate monitoring program be implemented.

The objective of the MNA monitoring program would be to provide ongoing confirmation that MNA is effectively addressing Site constituents, and allow for early detection of potential trend or evidence indicative of additional COI migration (if any). Table 6-1 presents a summary of the conceptual components of the MNA remedy including, but not limited to monitoring locations

(including two new proposed wells), COI and indicator parameter monitoring requirements, and frequency of monitoring.

**TABLE 6-1**  
**MONITORED NATURAL ATTENUATION COMPONENTS**  
**SOUTH CAVALCADE SUPERFUND SITE**  
**HOUSTON, TEXAS**

Component	North Area	South Area
Monitor plume centerline	MW-01 MW-24R MW-25	MW-08R MW-26 MW-27 <sup>(1)</sup> MW-28 <sup>(1)</sup>
Monitor locations for early detection of future advance of dissolved COIs	MW-25	MW-27 <sup>(2)</sup>
Monitor for early identification of concentration increases in plume centers	MW-01	MW-26
Monitoring Parameters (COIs)	PAHs BTEX	PAHs BTEX
Monitoring Parameters (known trends in MNA indicators)	ORP and pH Nitrate and Sulfate Iron and Manganese Total Organic Carbon	ORP and pH Nitrate and Sulfate Iron and Manganese Total Organic Carbon
Monitoring frequency over time <sup>(3)</sup>	Years 1-2: Quarterly Years 3-5: Annual Year 5+: Quinquennial	Years 1-2: Quarterly Years 3-5: Annual Year 5+: Quinquennial
Ongoing water usage and regulatory check <sup>(4)</sup>	Review well records Review status of groundwater use	Review well records Review status of groundwater use
Modification of the monitoring program	To Be Determined (Based on review and approval as monitoring program progresses)	To Be Determined (Based on review and approval as monitoring program progresses)

1. New monitoring wells (MW-27 & MW-28) proposed to be installed as sentinel well located downgradient of MW-26.
2. MW-27 is to be closest of the new sentinel monitoring wells proposed to be installed downgradient of MW-26.
3. Monitoring to be conducted quarterly for the first two years, once per year for the next 3 years, and once every five years thereafter. Quinquennial monitoring to be conducted in support of the USEPA 5-Year review process. Such monitoring to be completed approximately 6 months prior to issuance of the review to facilitate data collection/review.
4. Regulatory status as set forth by the City of Houston, HGCSO, and State of Texas)

Primary methods of analysis (i.e., those for the COIs) will be SW-846 Method 8260B (BTEX) and SW-846 Method 8270C (PAHs including naphthalene). Nitrate, sulfate, dissolved iron, dissolved manganese, and Total Organic Carbon will be analyzed using EPA Methods 353.2, 375.4, 6010, 6010, and 415.1, respectively. Additional details on the proposed monitoring program will be presented in the Proposed Plan. As part of the Remedial Design process, a groundwater monitoring plan will be prepared that will include all of the specific requirements for the groundwater monitoring program.

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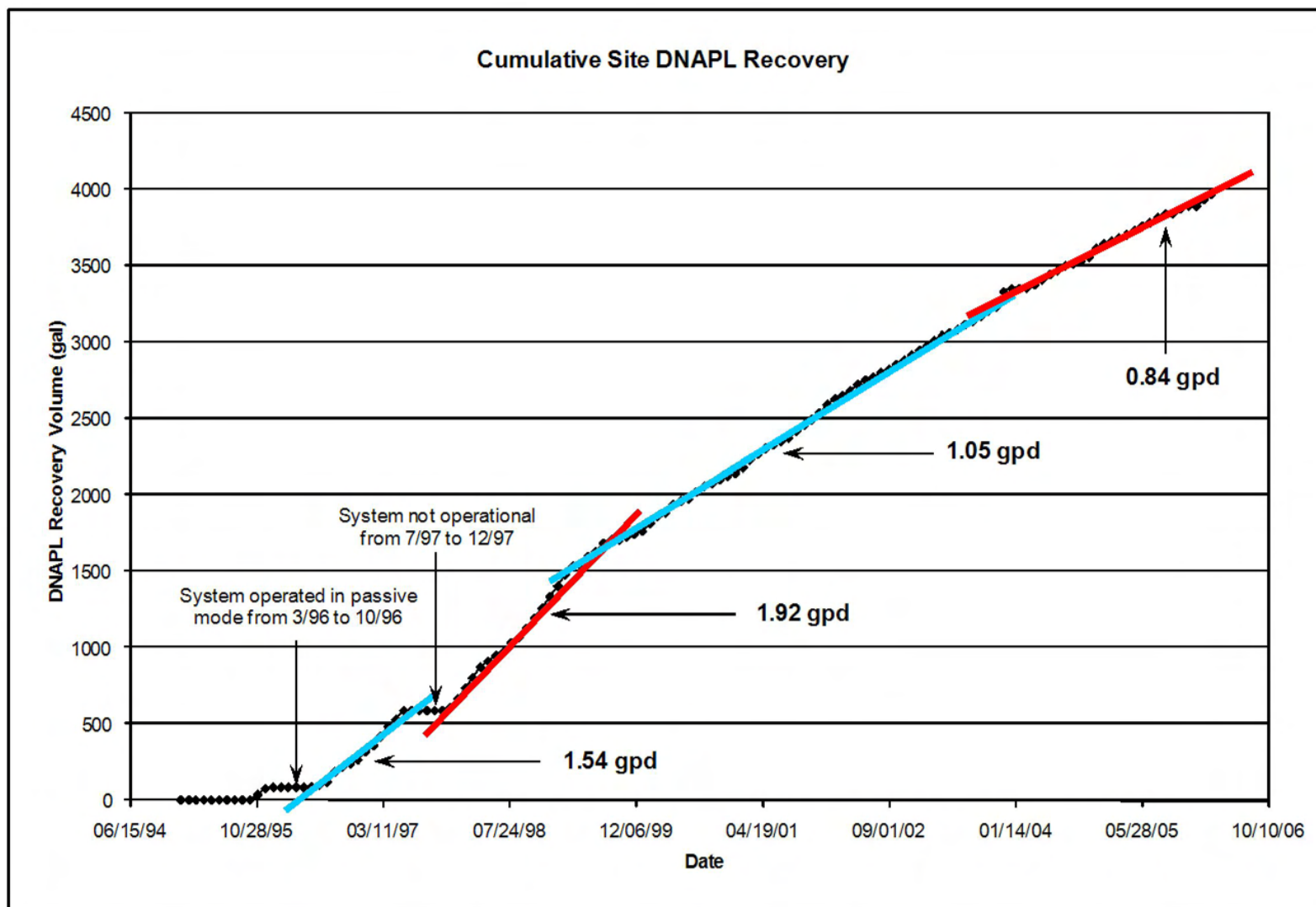
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INCORPORATED

NA TECHNICAL MEMORANDUM  
SOUTH CAVALCADE SUPERFUND SITE  
HOUSTON, TEXAS

REFERENCE:

ISSUE DATE:

KEY ENVIRONMENTAL, INC.  
200 THIRD AVENUE  
CARNEGIE, PA 15106

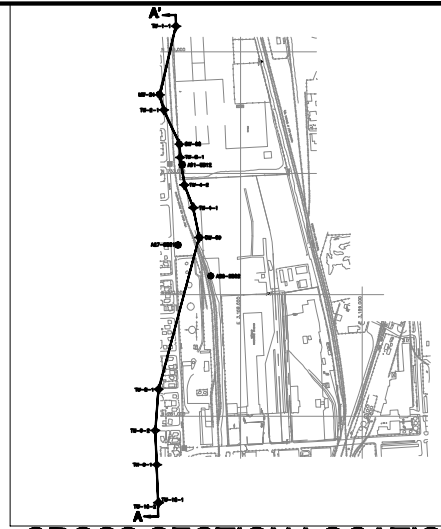
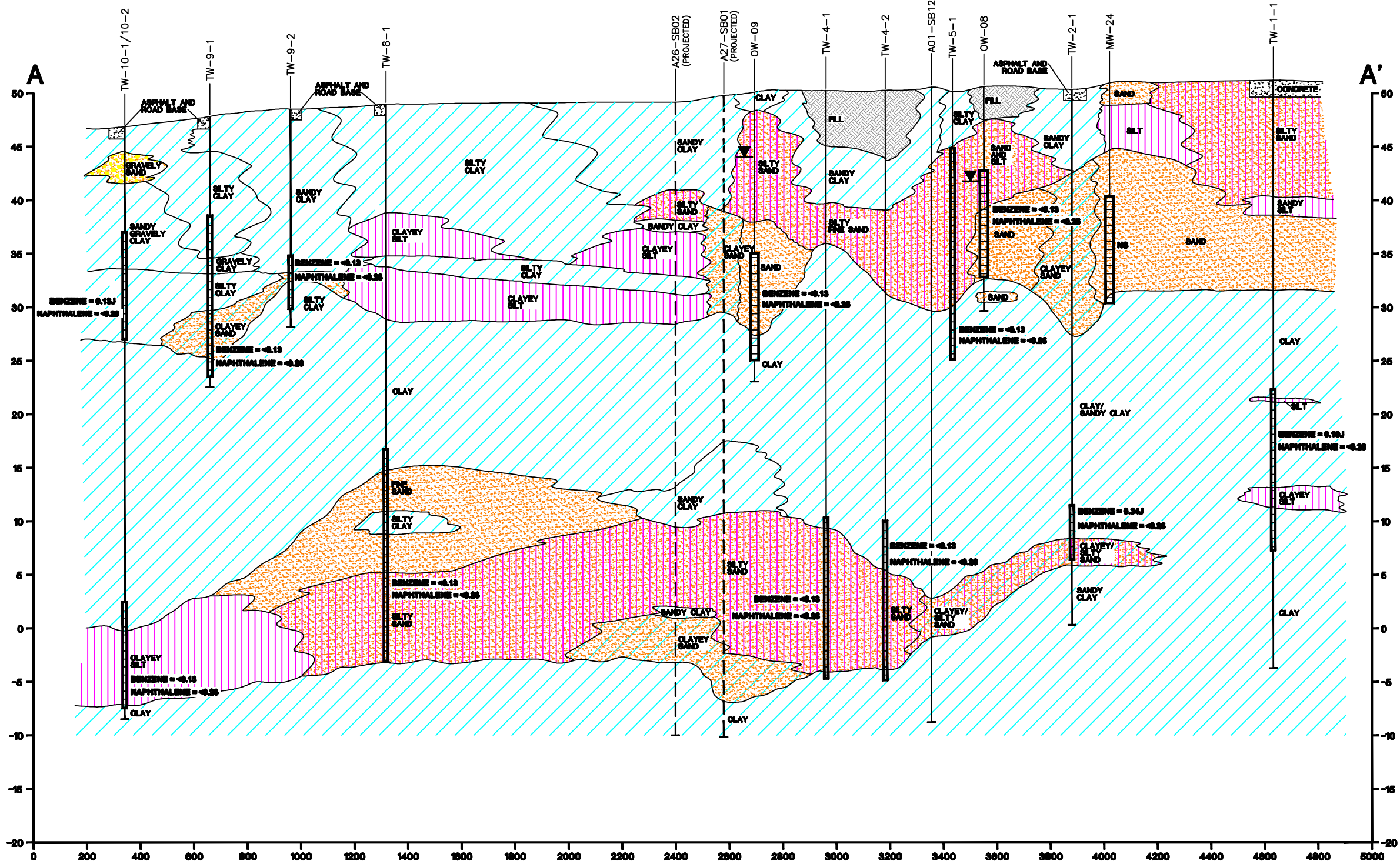
TOTAL CUMULATIVE  
DNAPL RECOVERY

PROJECT NO: 11-233

FIGURE 1-1

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CROSS SECTION LOCATION

LEGEND

- GRAVELLY SAND
- CONCRETE, ASPHALT AND ROAD BASE
- FILL
- SAND
- SILT, CLAYEY SILT, SANDY SILT
- SILTY SAND
- CLAY, SANDY CLAY, SILTY CLAY
- CLAYEY SAND

WATER LEVEL MEASURED 9/16 - 9/17 2005

SOIL BORING LOCATION

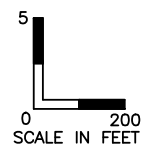
MONITORING WELL/SCREEN INTERVAL LOCATION

BENZENE = ug/L  
NAPHTHALENE = ug/L

TEMPORARY WELL/SCREEN INTERVAL LOCATION

BENZENE = ug/L  
NAPHTHALENE = ug/L

NOTES:  
NS - NOT SAMPLED, UNABLE TO LOCATE WELL



REV #	DATE	DESCRIPTION	APPD

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BEAZER EAST, INC.  
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SOUTH CAVALCADE SUPERFUND SITE  
HOUSTON, TEXAS

GEOLOGIC CROSS SECTION A-A'

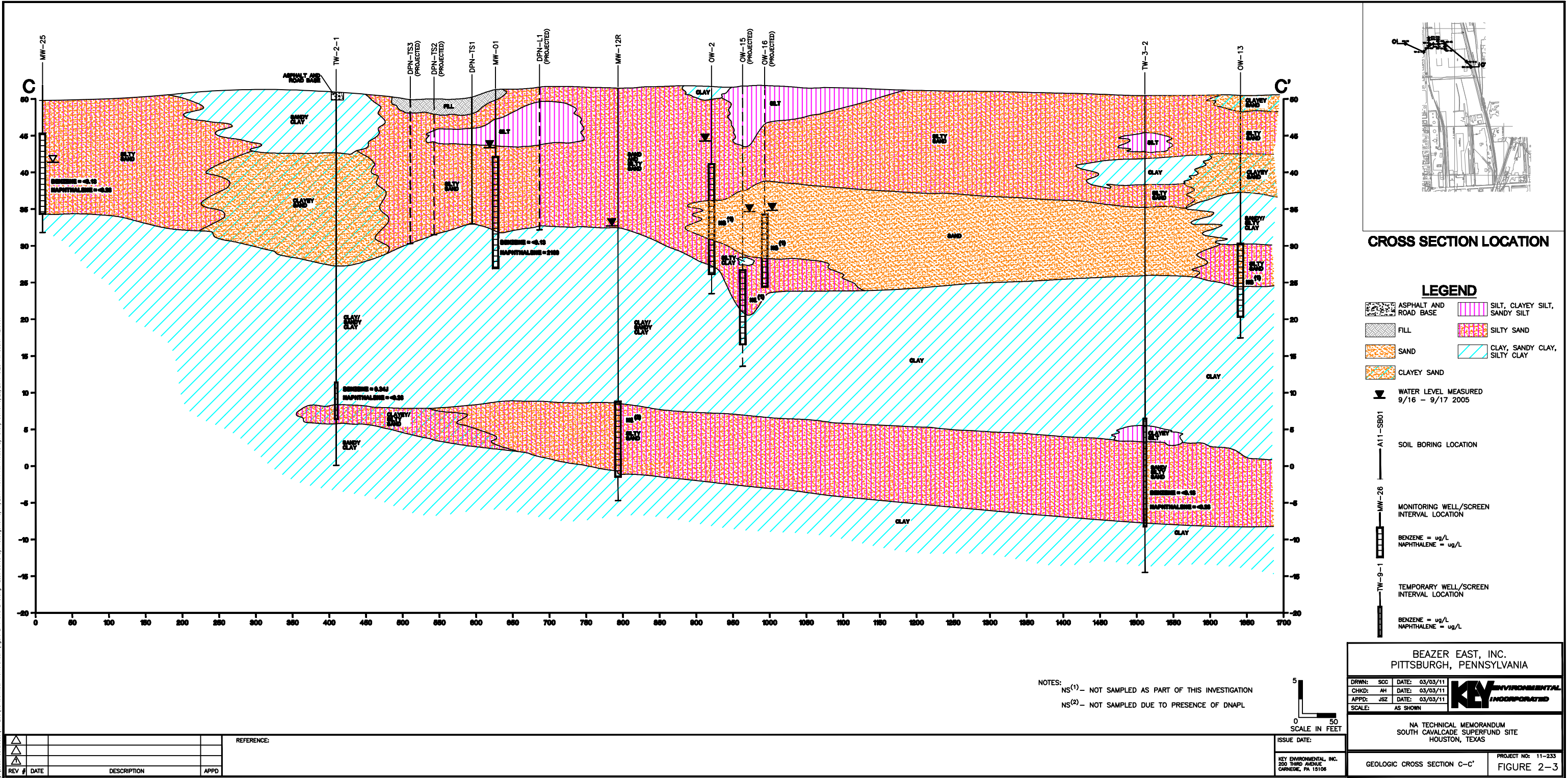
PROJECT NO: 11-233  
FIGURE 2-1

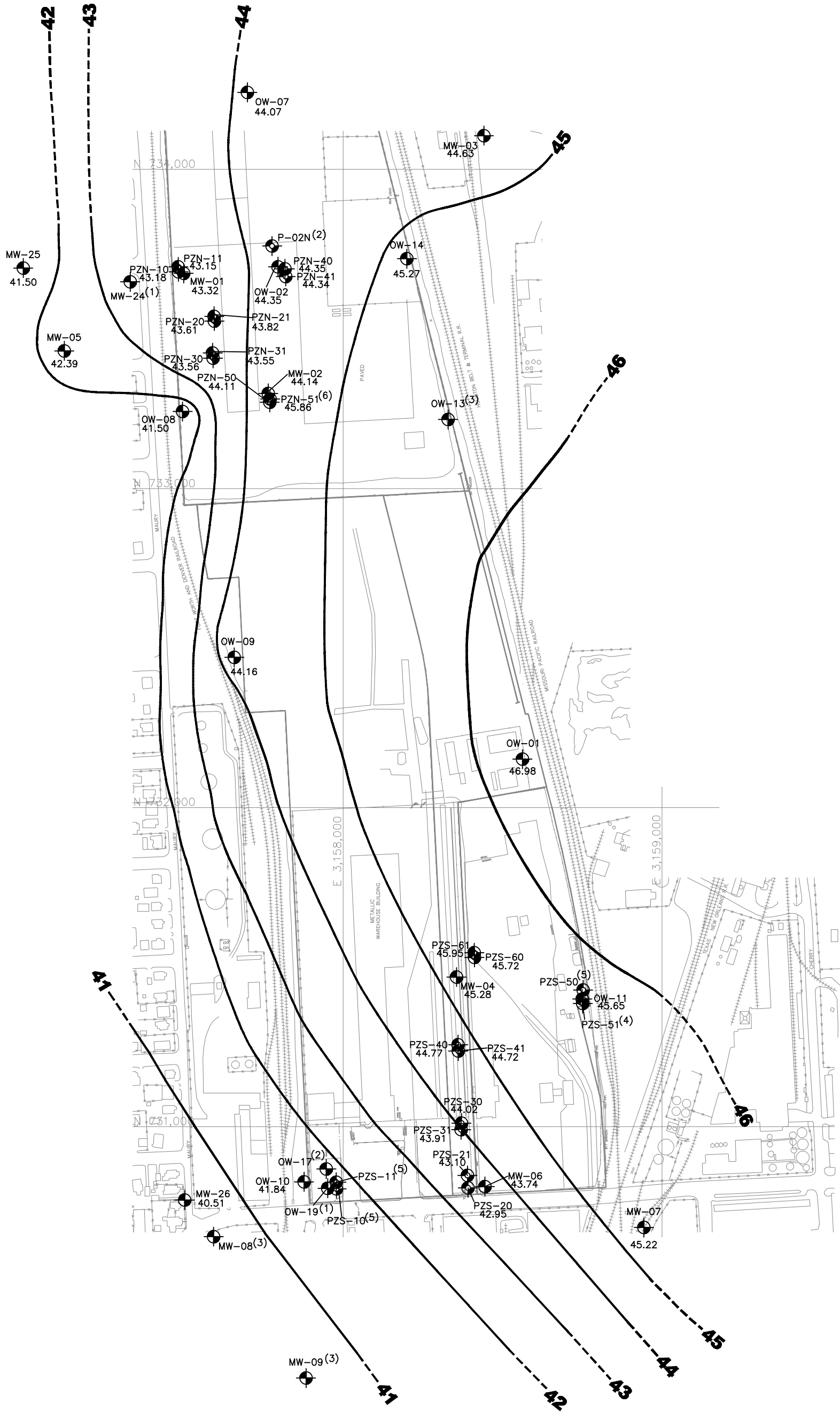








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LEGEND:

-  MW-09  
MONITORING WELL LOCATION
-  45  
POTENTIOMETRIC SURFACE CONTOURS (FT-MSL) CONTOUR INTERVAL = 1'
- 44.16  
POTENTIOMETRIC SURFACE ELEVATION (FT-MSL)

NOTES:

- (1) DAMAGED WELL. UNABLE TO COLLECT MEASUREMENT
- (2) WELL NEEDS SURVEYED TO OBTAIN MEASURING POINT ELEVATION
- (3) WELL COULD NOT BE LOCATED
- (4) WELL UNDER JERSEY BARRIER – UNABLE TO COLLECT MEASUREMENT
- (5) WELLS PZS-50, PZS-11, AND PZS-10 NOT USED IN CONTOURING DUE TO FLUCTUATIONS IN WATER LEVELS CAUSED BY NEARBY PUMPING
- (6) WELL PZN-51 NOT USED IN CONTOURING WATER LEVEL ELEVATION SUSPECT

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PITTSBURGH, PENNSYLVANIA

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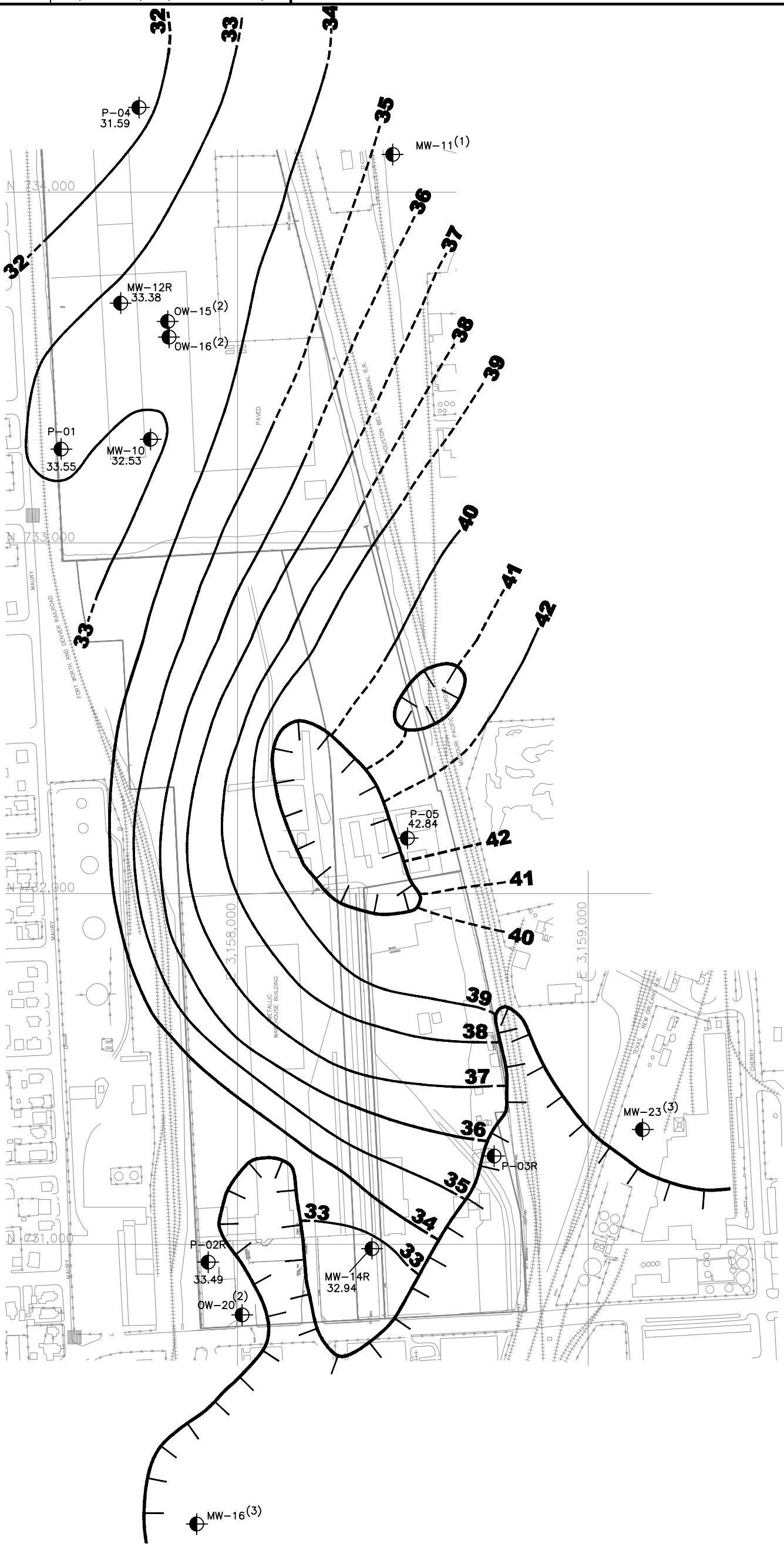


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SOUTH CAVALCADE SUPERFUND SITE  
HOUSTON, TEXAS

POTENTIOMETRIC SURFACE ELEVATION  
CONTOUR MAP  
SHALLOW AQUIFER 9/16-17/2005

PROJECT NO: 11-233  
FIGURE 2-4





LEGEND:

- MW-10  
MONITORING WELL LOCATION
- 40— POTENTIOMETRIC SURFACE CONTOURS (FT-MSL) CONTOUR INTERVAL = 1'
- 32.53 POTENTIOMETRIC SURFACE ELEVATION (FT-MSL)
- INTERMEDIATE ZONE SAND IS ABSENT (4)

NOTES:

- (1) DAMAGED WELL. UNABLE TO COLLECT MEASUREMENT
- (2) WELL NEEDS SURVEYED TO OBTAIN MEASURING POINT ELEVATION
- (3) WELL COULD NOT BE LOCATED
- (4) AREA WHERE INTERMEDIATE ZONE SAND IS ABSENT TAKEN FROM MAPPING PREPARED BY EPA AND PRESENTED DURING THE SEPTEMBER 8, 2004 MEETING

BEAZER EAST, INC.  
PITTSBURGH, PENNSYLVANIA

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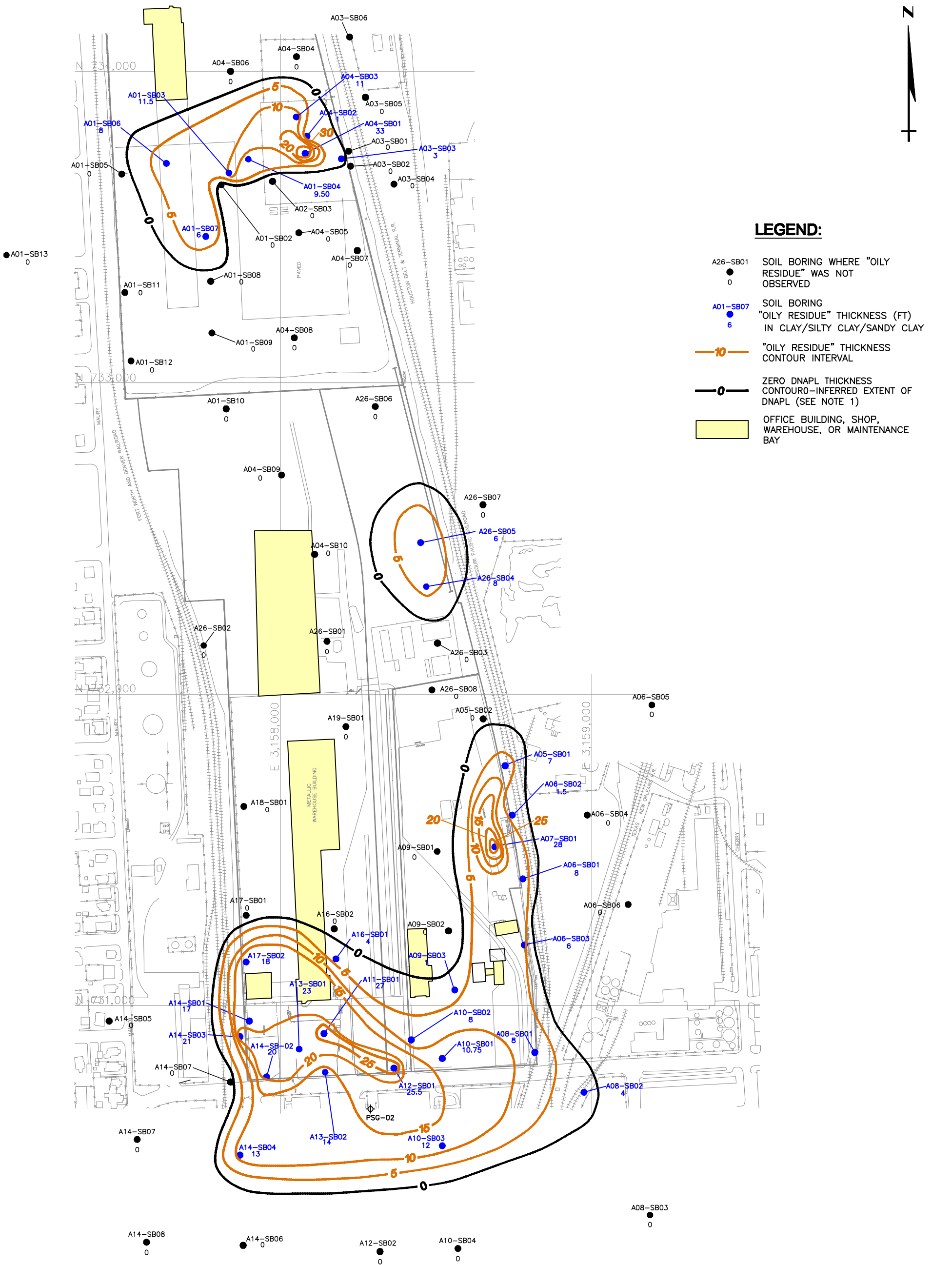
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SOUTH CAVALCADE SUPERFUND SITE  
HOUSTON, TEXAS

POTENTIOMETRIC SURFACE ELEVATION  
CONTOUR MAP  
INTERBEDDED AQUIFER ZONE 9/16-17-2005

PROJECT No: 11-233  
FIGURE 2-5



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NOTE:

1. THE ZERO CONTOUR DEPICTS THE INFERRED EXTENT OF THE POTENTIAL DNAPL SOURCE AREA (PDSA) IN THE INTERMEDIATE AQUITARD. INFERRED EXTENT BASED ON VISUAL OBSERVATION, MEASURED DNAPL IN MONITORING WELLS, TOTAL PAH CONCENTRATIONS > 100 MG/KG, OR SURROGATE TOTAL AROMATIC HYDROCARBON CONCENTRATIONS > 1000 MG/KG.

0 300 600  
FEET

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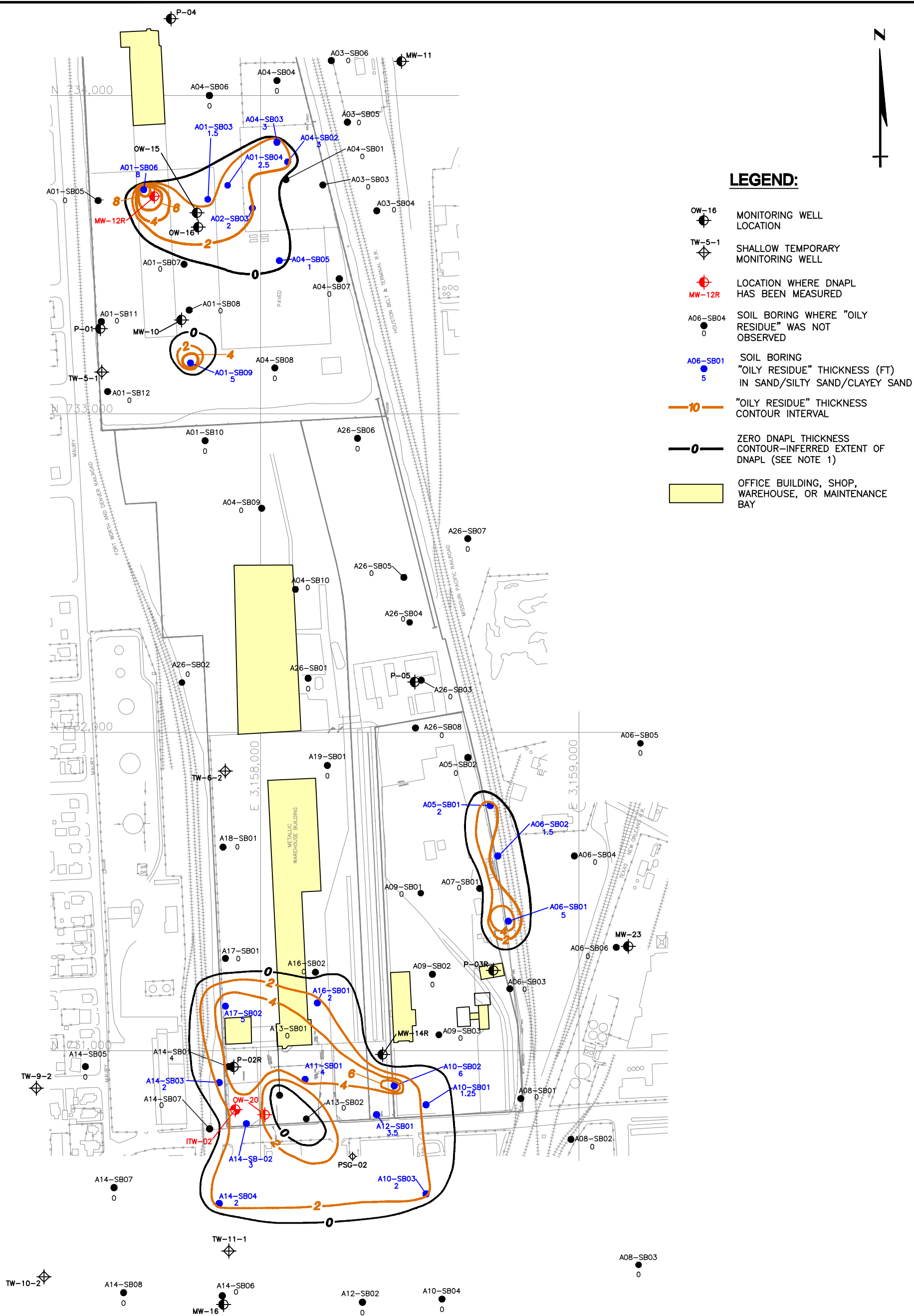


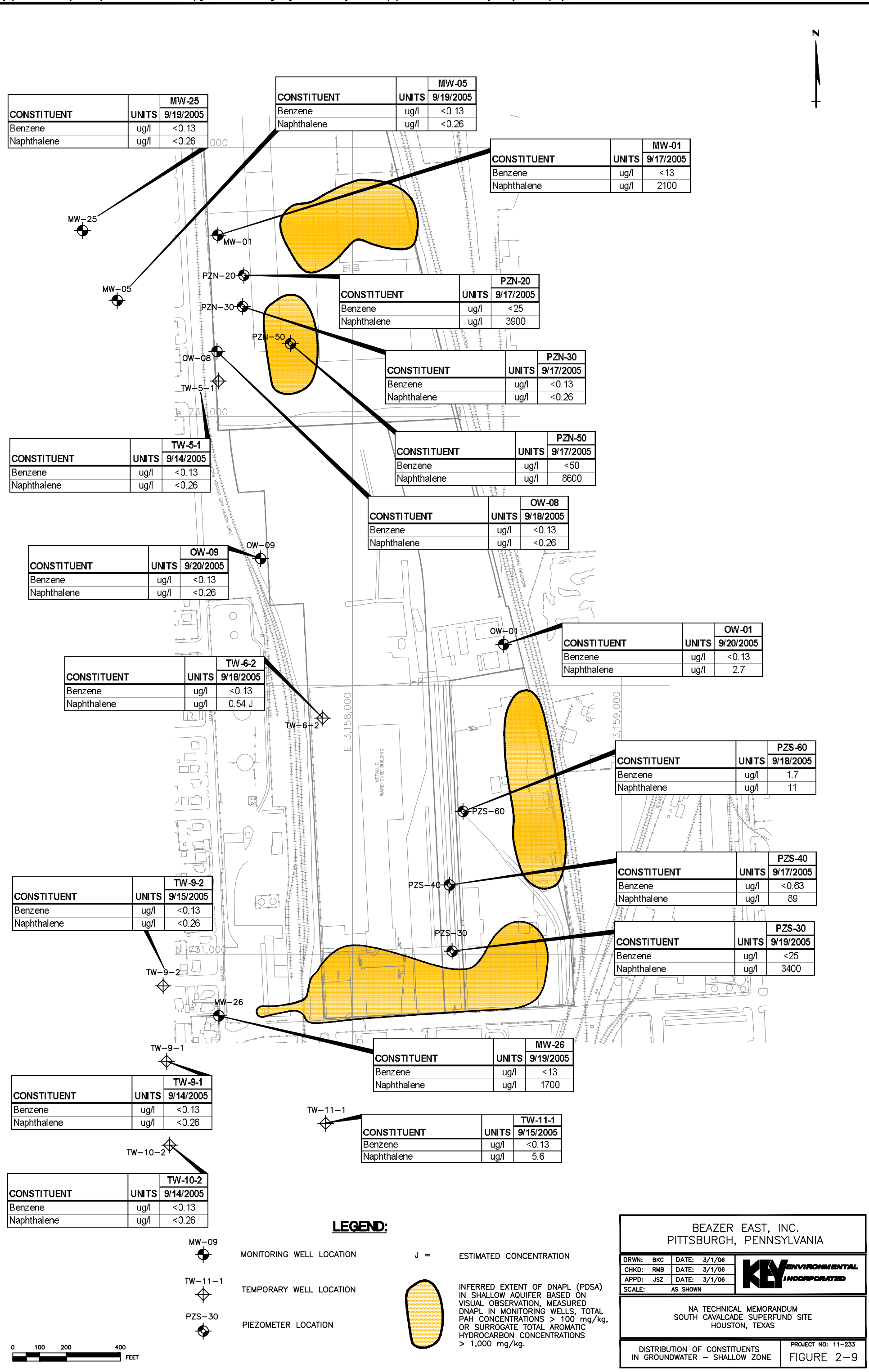
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ESTIMATED SOURCE EXTENT  
IN THE INTERMEDIATE AQUITARD

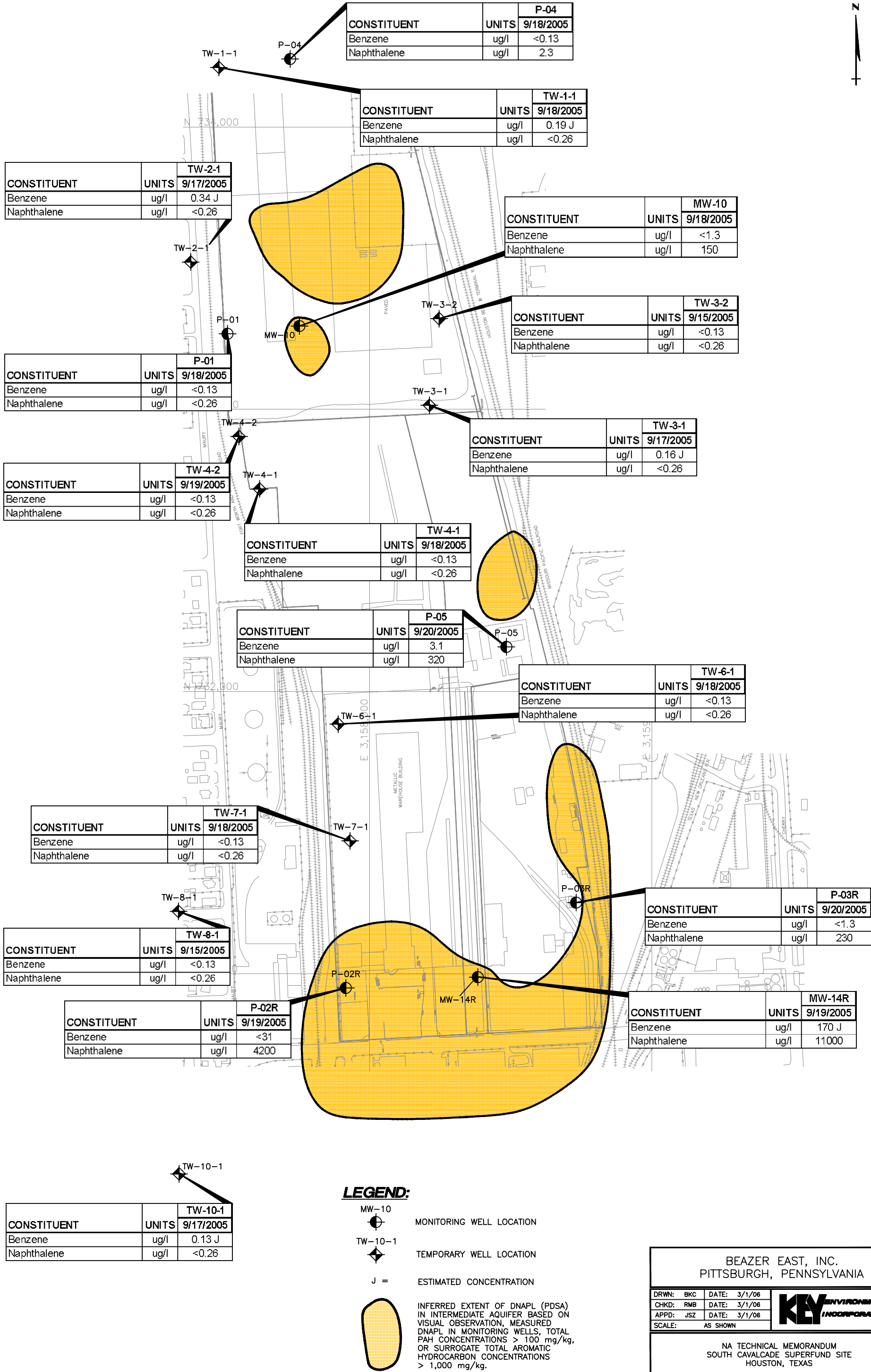
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FIGURE 2-7





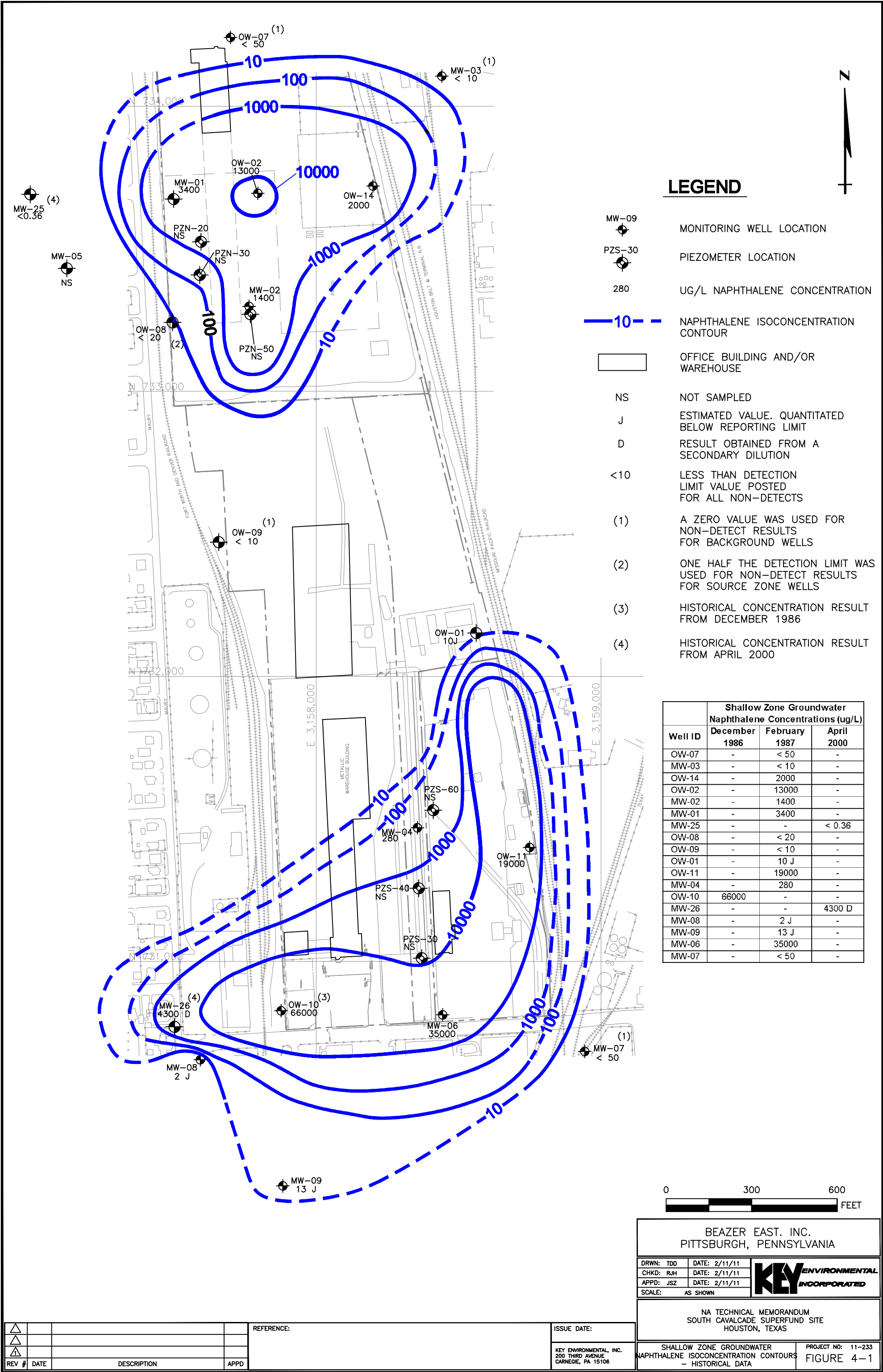






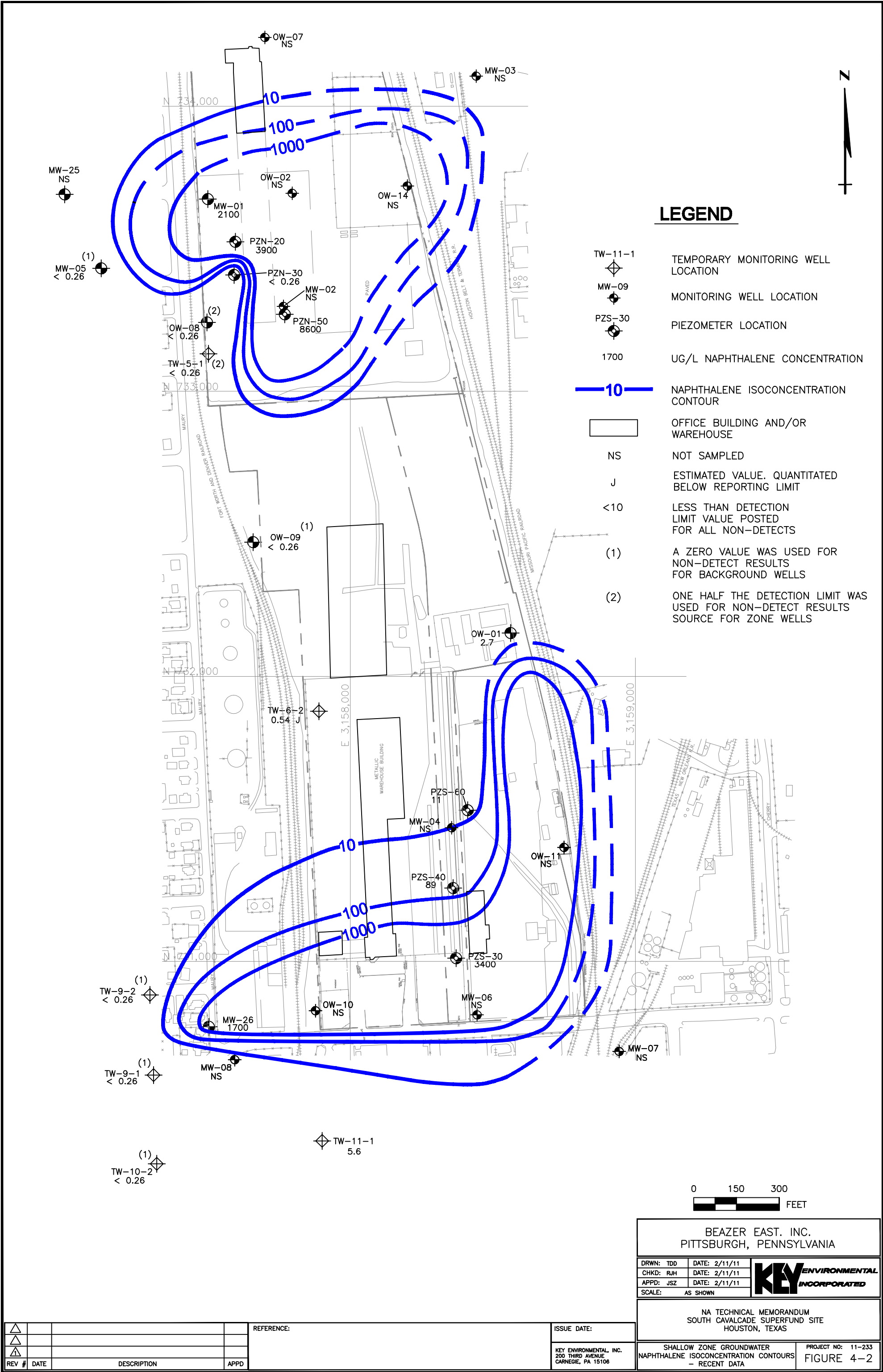


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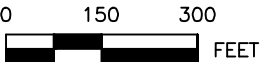
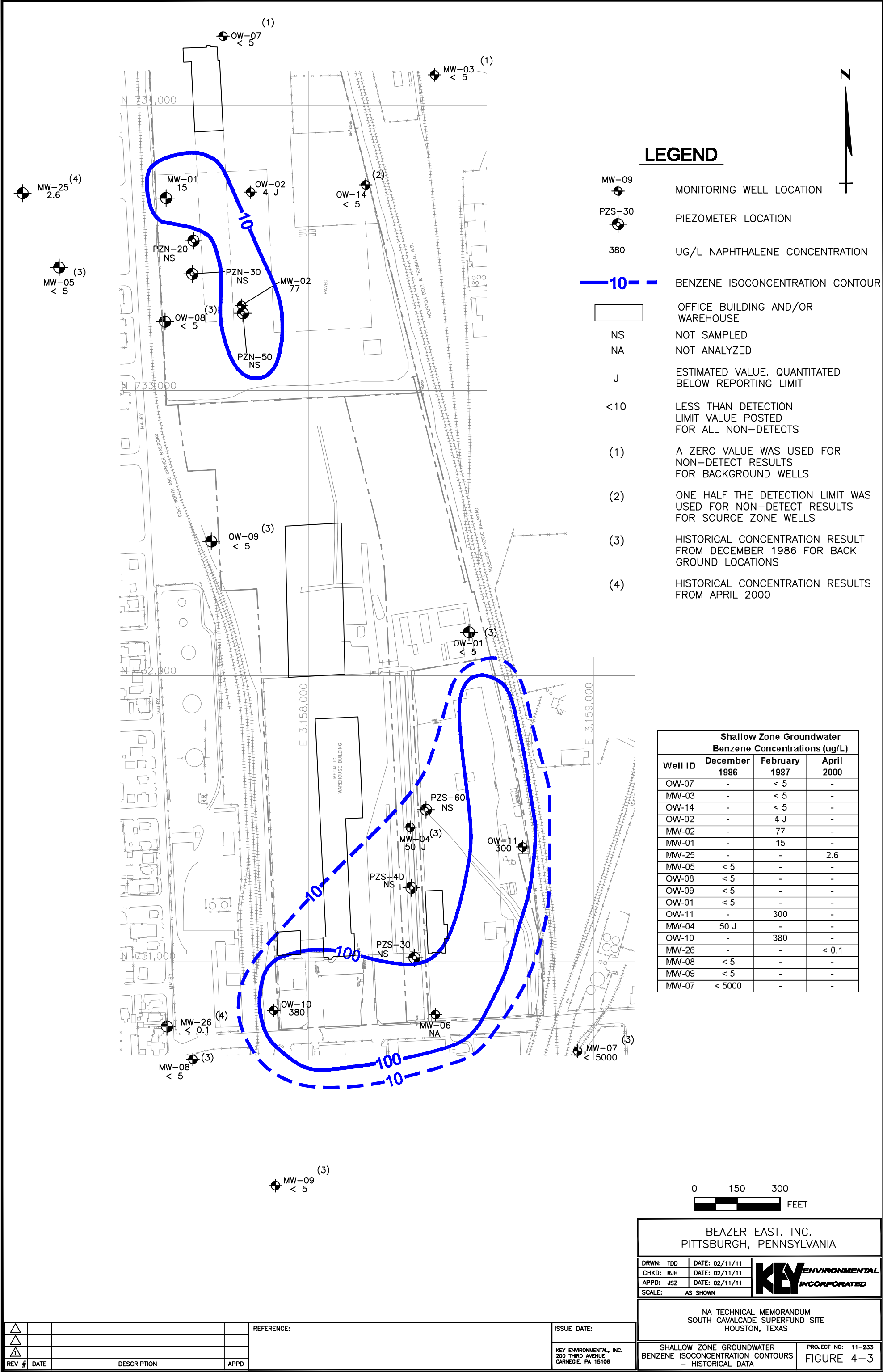


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REV #	DATE	DESCRIPTION	APPD		KEY ENVIRONMENTAL, INC. 200 THIRD AVENUE CARNEGIE, PA 15106		SHALLOW ZONE GROUNDWATER NAPHTHALENE ISOCONCENTRATION CONTOURS — HISTORICAL DATA	
							PROJECT NO: 11-233 FIGURE 4-1	

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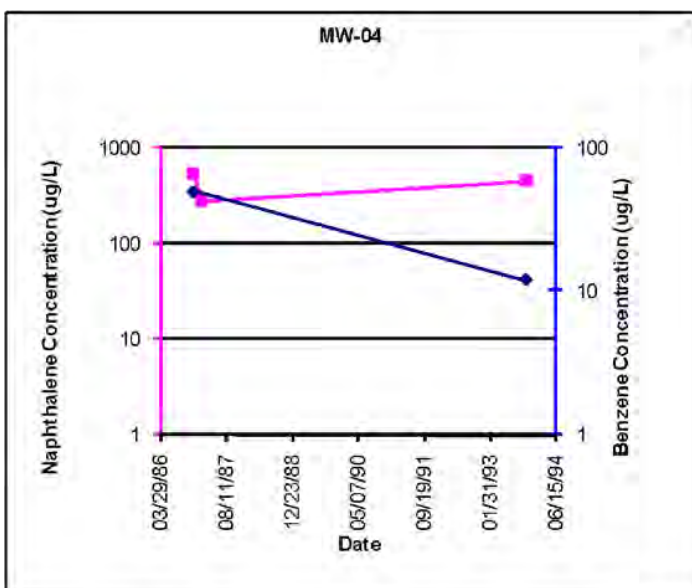
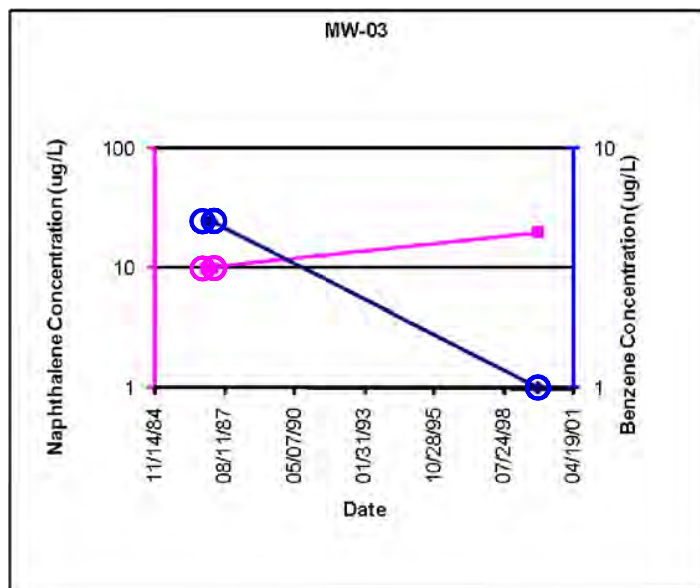
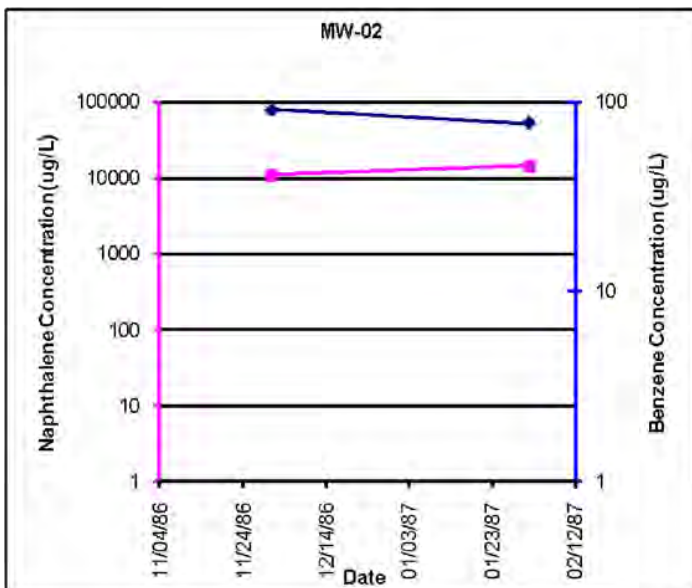
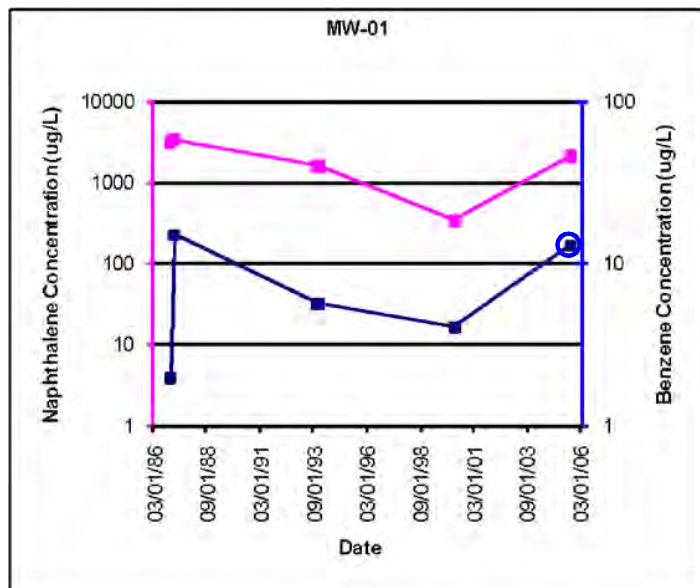
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SHALLOW ZONE GROUNDWATER BENZENE ISOCONCENTRATION CONTOURS - HISTORICAL DATA	PROJECT NO: 11-233 FIGURE 4-3
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- NAPHTHALENE
- ◆ BENZENE
- ◻ NON-DETECT FOR NAPHTHALENE;  
VALUE REPRESENTS REPORTING LIMIT
- ◻ NON-DETECT FOR BENZENE;  
VALUE REPRESENTS REPORTING LIMIT

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NAPHTHALENE AND BENZENE

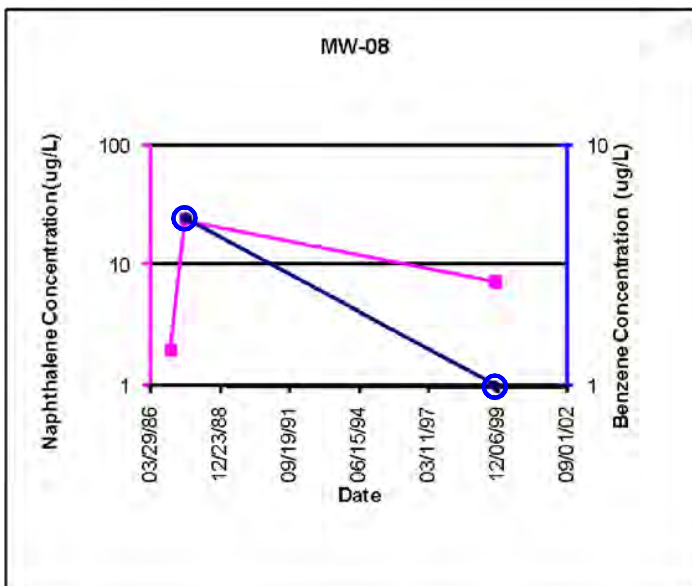
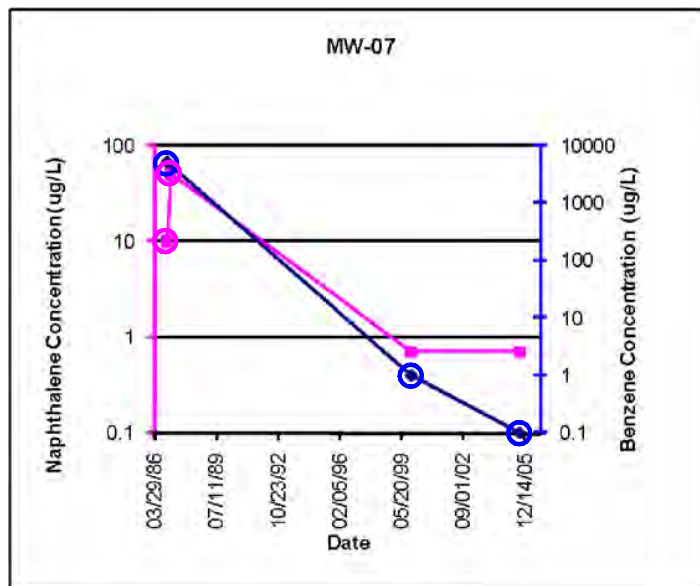
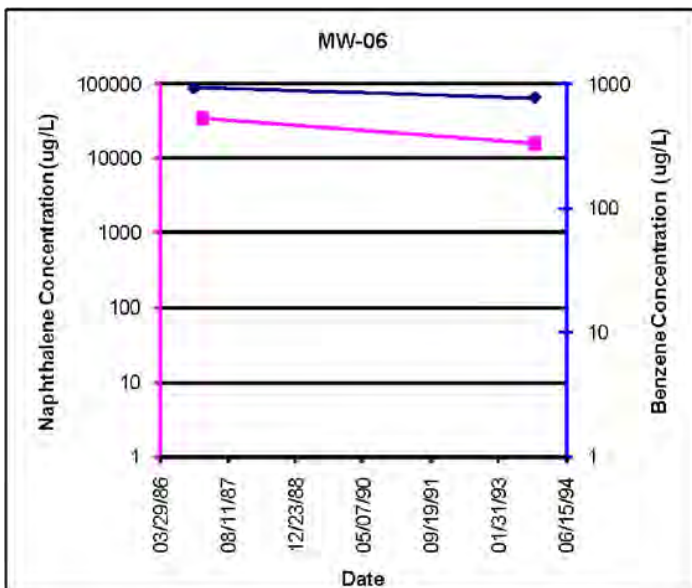
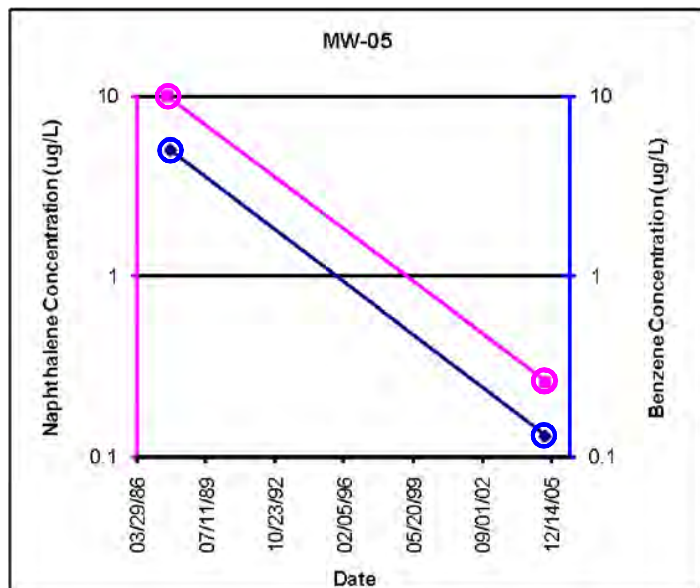
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FIGURE 4-5A

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### LEGEND

- NAPHTHALENE
- ◆ BENZENE
- NON-DETECT FOR NAPHTHALENE;  
VALUE REPRESENTS REPORTING LIMIT
- ◇ NON-DETECT FOR BENZENE;  
VALUE REPRESENTS REPORTING LIMIT

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NAPHTHALENE AND BENZENE

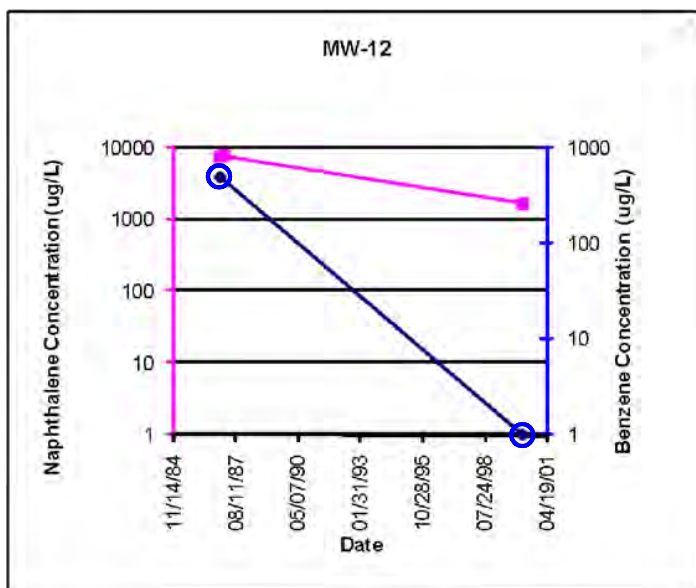
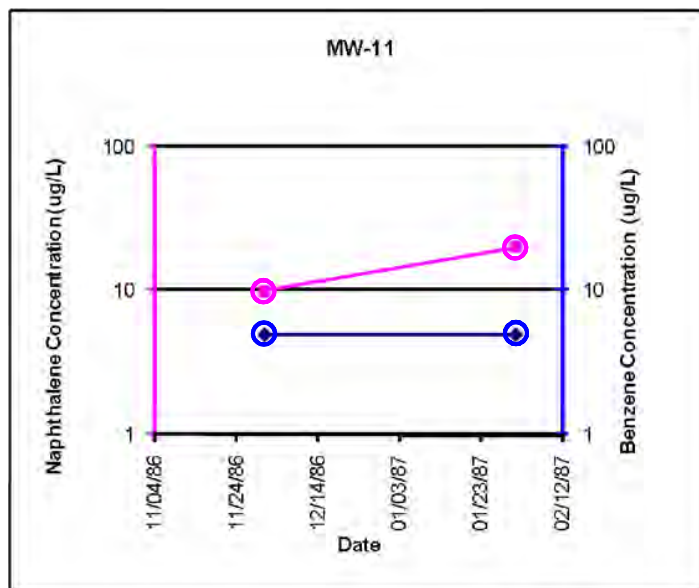
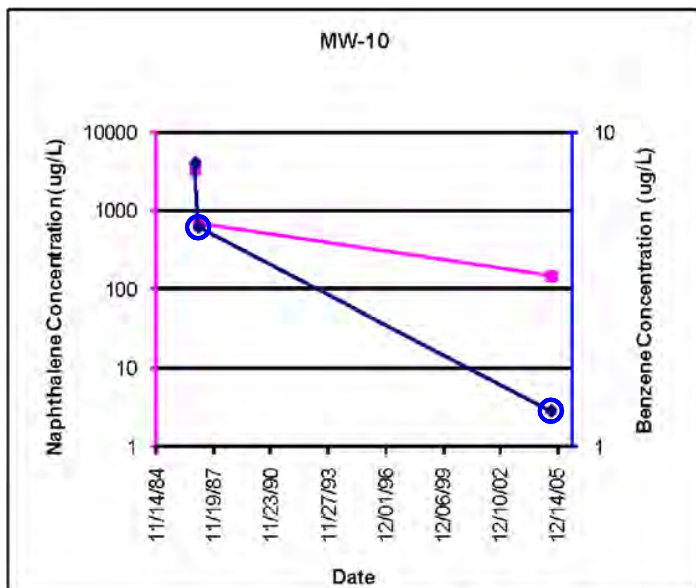
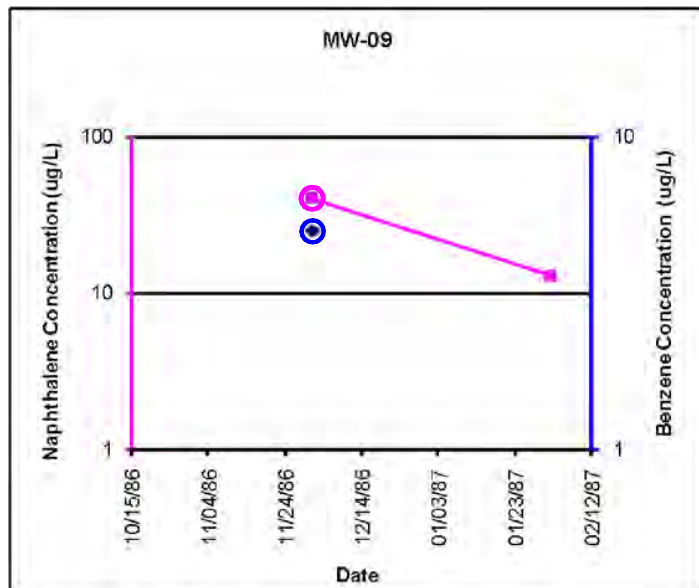
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FIGURE 4-5B

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**LEGEND:**

- NAPHTHALENE
- ◆ BENZENE
- (pink) NON-DETECT FOR NAPHTHALENE; VALUE REPRESENTS REPORTING LIMIT
- (blue) NON-DETECT FOR BENZENE; VALUE REPRESENTS REPORTING LIMIT

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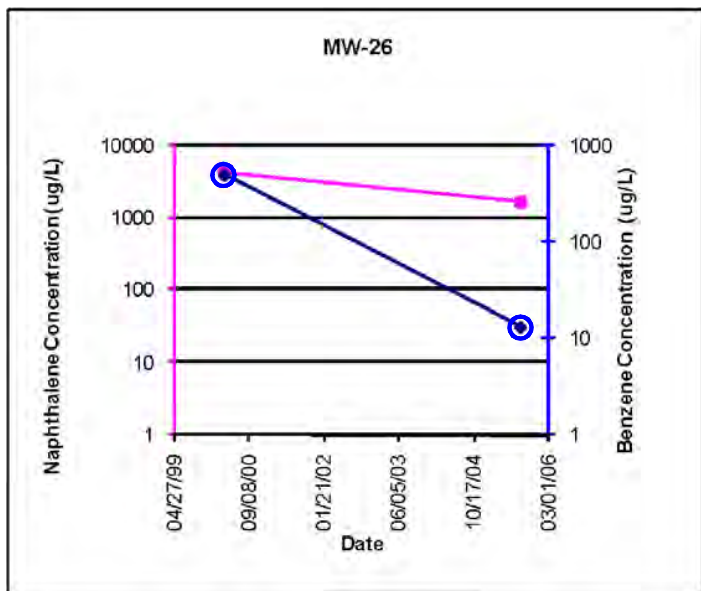
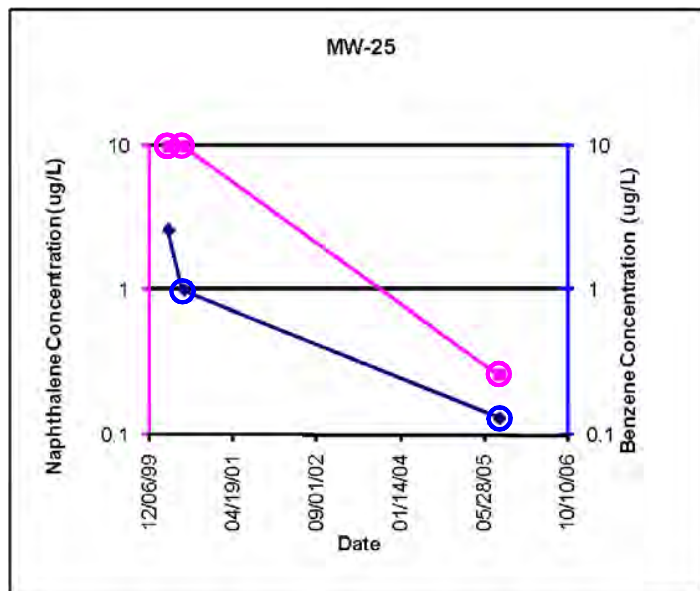
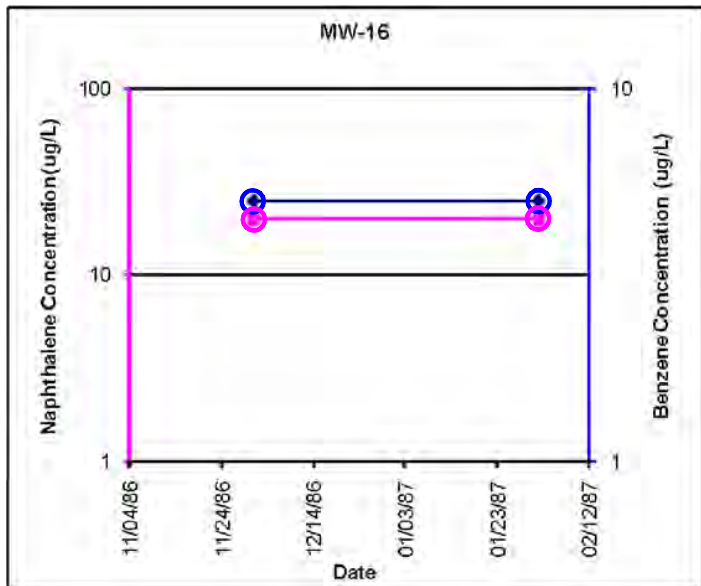
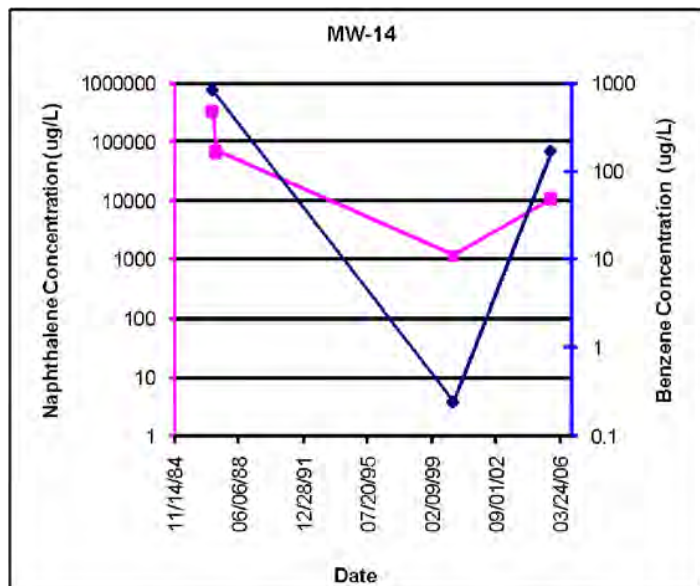
TIME SERIES PLOTS OF  
NAPHTHALENE AND BENZENE

PROJECT NO: 11-233  
FIGURE 4-5C

REFERENCE:

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**LEGEND:**

- NAPHTHALENE
- ◆ BENZENE
- (pink) NON-DETECT FOR NAPHTHALENE; VALUE REPRESENTS REPORTING LIMIT
- (blue) NON-DETECT FOR BENZENE; VALUE REPRESENTS REPORTING LIMIT

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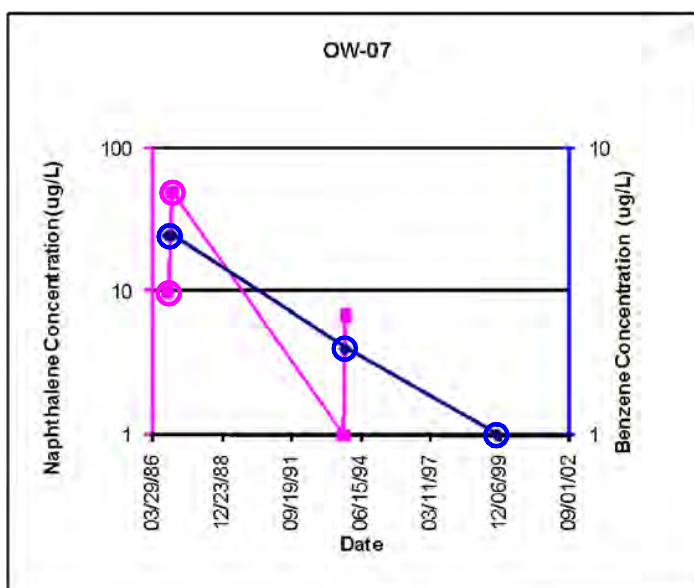
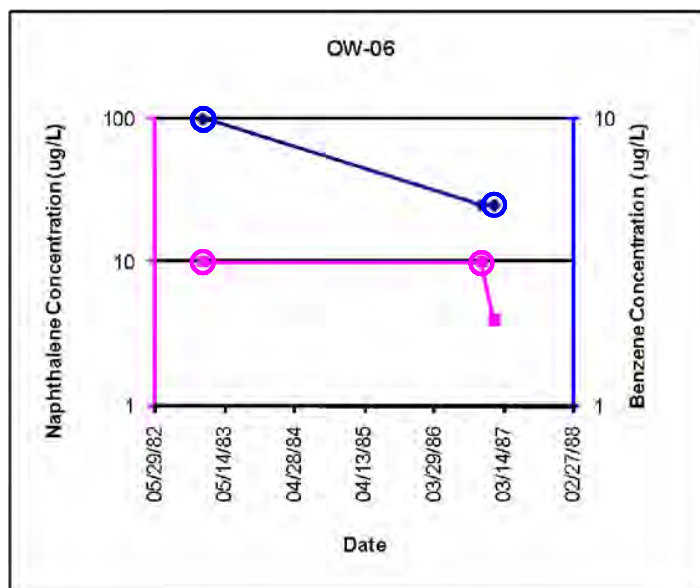
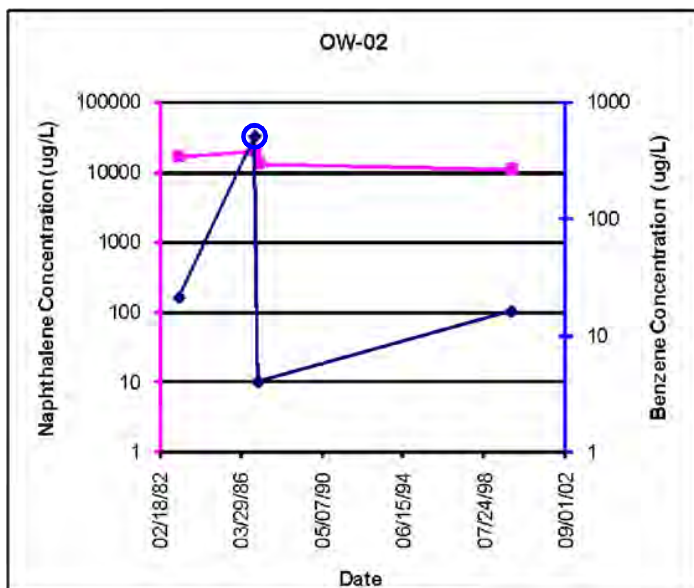
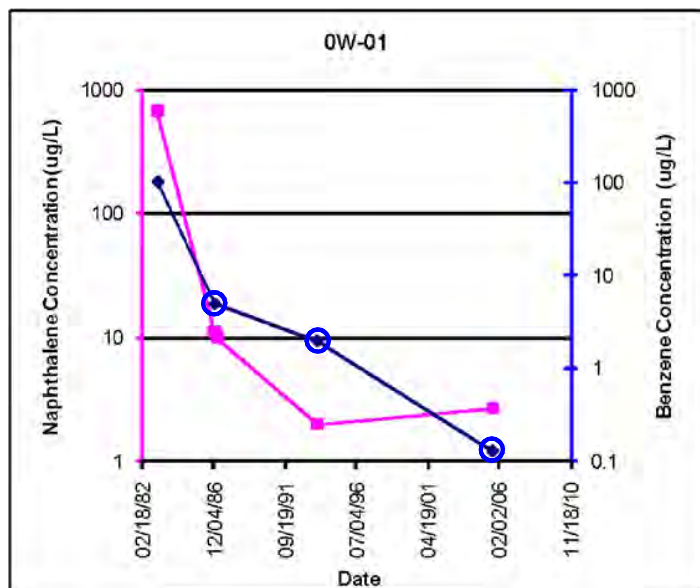
TIME SERIES PLOTS OF  
NAPHTHALENE AND BENZENE

PROJECT NO: 11-233  
FIGURE 4-5D

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- ◻ NON-DETECT FOR NAPHTHALENE;  
VALUE REPRESENTS REPORTING LIMIT
- ◻ NON-DETECT FOR BENZENE;  
VALUE REPRESENTS REPORTING LIMIT

BEAZER EAST, INC.  
PITTSBURGH, PENNSYLVANIA

DRWN: TDD	DATE: 02/11/11
CHKD: RJH	DATE: 02/11/11
APPD: JSZ	DATE: 02/11/11
SCALE: NOT TO SCALE	

**KEY** ENVIRONMENTAL  
INCORPORATED

NA TECHNICAL MEMORANDUM  
SOUTH CAVALCADE SUPERFUND SITE  
HOUSTON, TEXAS

TIME SERIES PLOTS OF  
NAPHTHALENE AND BENZENE

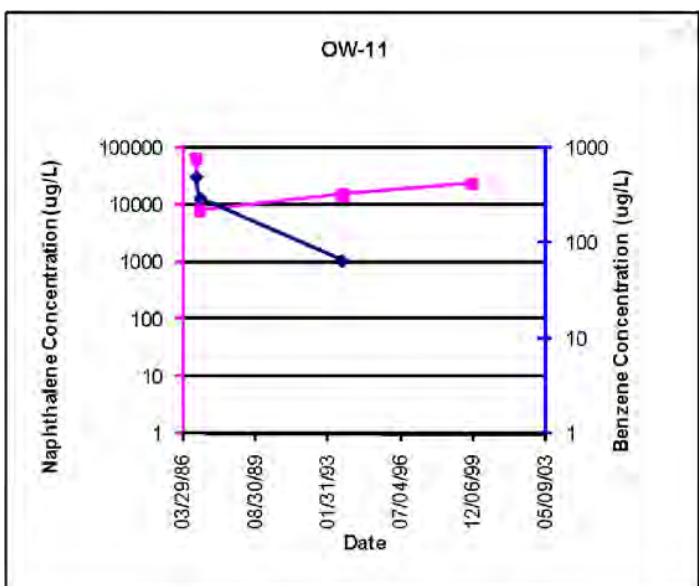
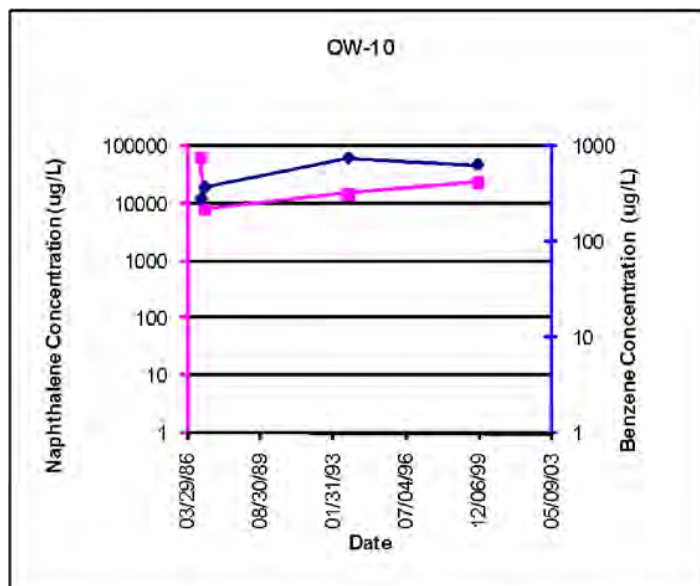
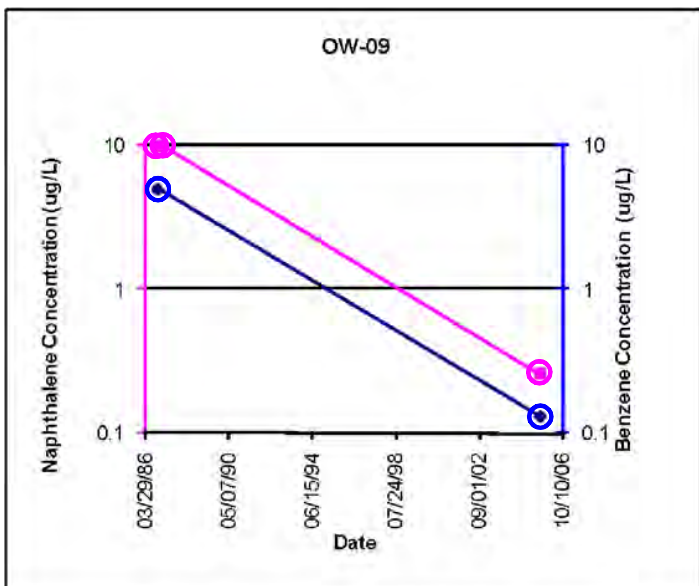
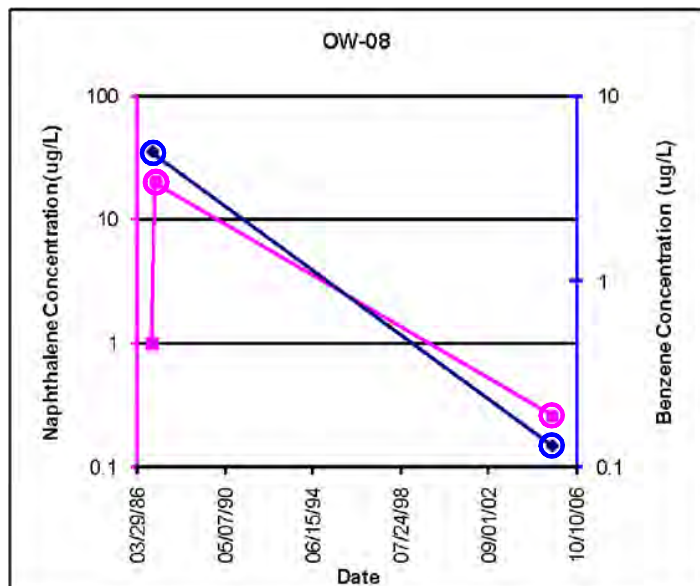
PROJECT NO: 11-233

FIGURE 4-5E

REFERENCE:

ISSUE DATE:

KEY ENVIRONMENTAL, INC.  
200 THIRD AVENUE  
CARNEGIE, PA 15106



### LEGEND

- NAPHTHALENE
- ◆ BENZENE
- NON-DETECT FOR NAPHTHALENE; VALUE REPRESENTS REPORTING LIMIT
- ◇ NON-DETECT FOR BENZENE; VALUE REPRESENTS REPORTING LIMIT

BEAZER EAST, INC.  
PITTSBURGH, PENNSYLVANIA

DRWN: TDD	DATE: 02/11/11
CHKD: RJH	DATE: 02/11/11
APPD: JSZ	DATE: 02/11/11
SCALE: NOT TO SCALE	

**KEY** ENVIRONMENTAL  
INCORPORATED

NA TECHNICAL MEMORANDUM  
SOUTH CAVALCADE SUPERFUND SITE  
HOUSTON, TEXAS

TIME SERIES PLOTS OF  
NAPHTHALENE AND BENZENE

PROJECT NO: 11-233

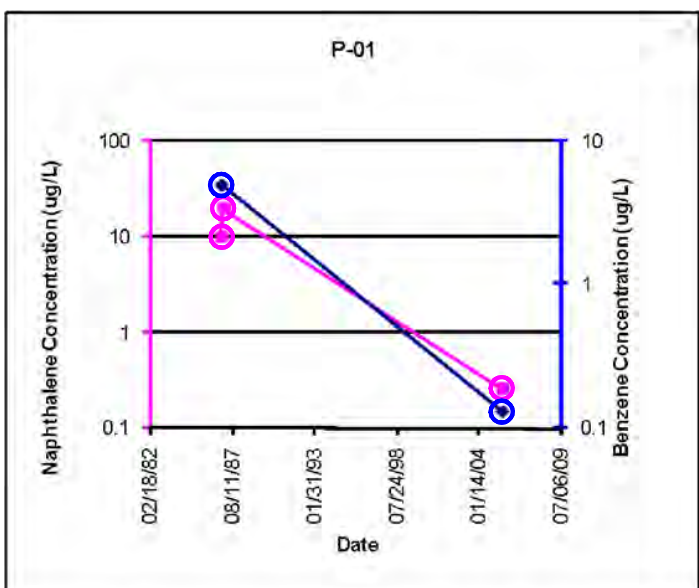
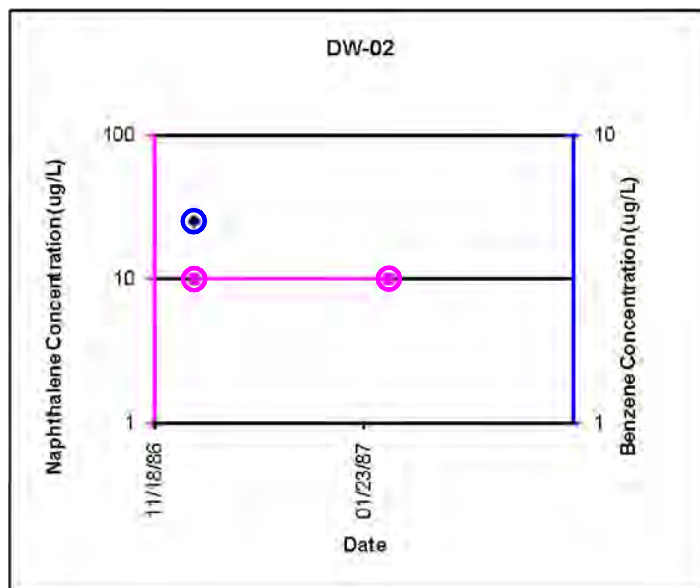
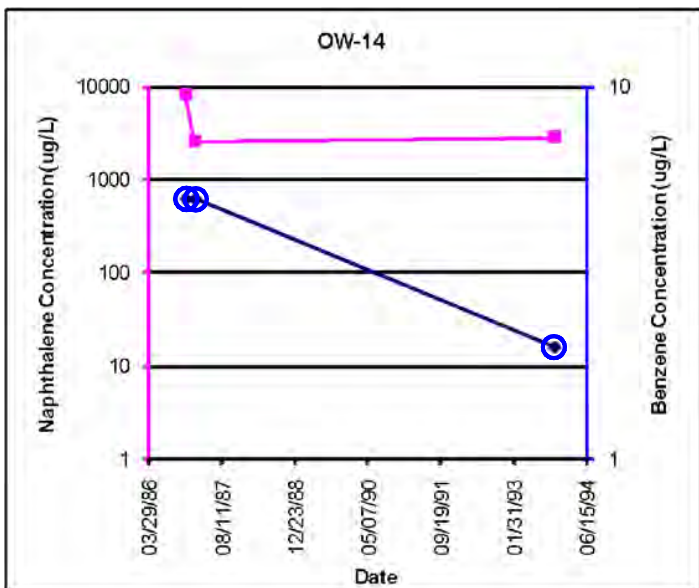
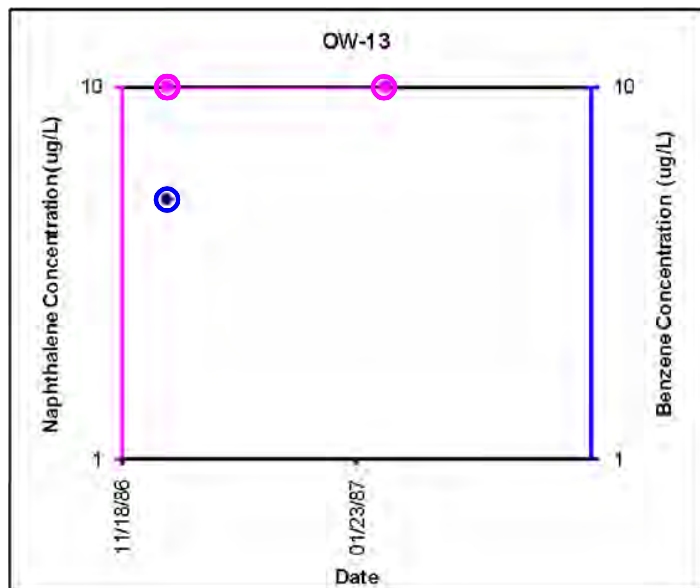
FIGURE 4-5F

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ISSUE DATE:

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200 THIRD AVENUE  
CARNEGIE, PA 15106





### LEGEND

- NAPHTHALENE
- ◆ BENZENE
- ◻ NON-DETECT FOR NAPHTHALENE;  
VALUE REPRESENTS REPORTING LIMIT
- ◻ NON-DETECT FOR BENZENE;  
VALUE REPRESENTS REPORTING LIMIT

BEAZER EAST, INC.  
PITTSBURGH, PENNSYLVANIA

DRWN: TDD	DATE: 02/11/11
CHKD: RJH	DATE: 02/11/11
APPD: JSZ	DATE: 02/11/11
SCALE: NOT TO SCALE	

**KEY** ENVIRONMENTAL  
INCORPORATED

NA TECHNICAL MEMORANDUM  
SOUTH CAVALCADE SUPERFUND SITE  
HOUSTON, TEXAS

TIME SERIES PLOTS OF  
NAPHTHALENE AND BENZENE

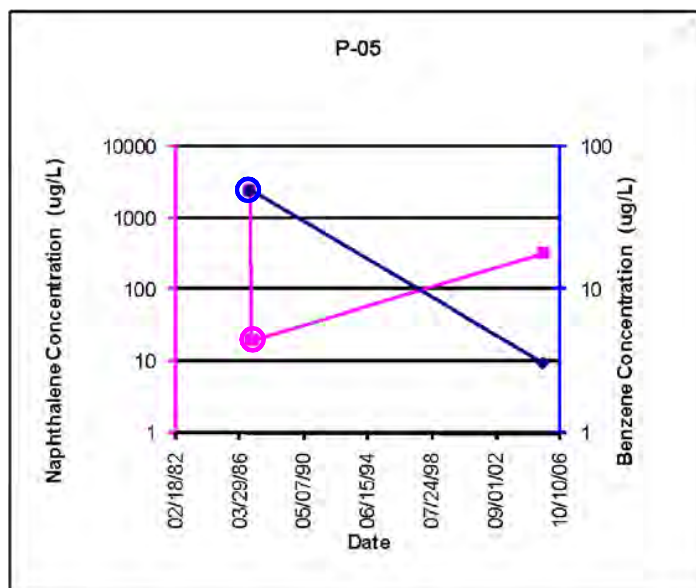
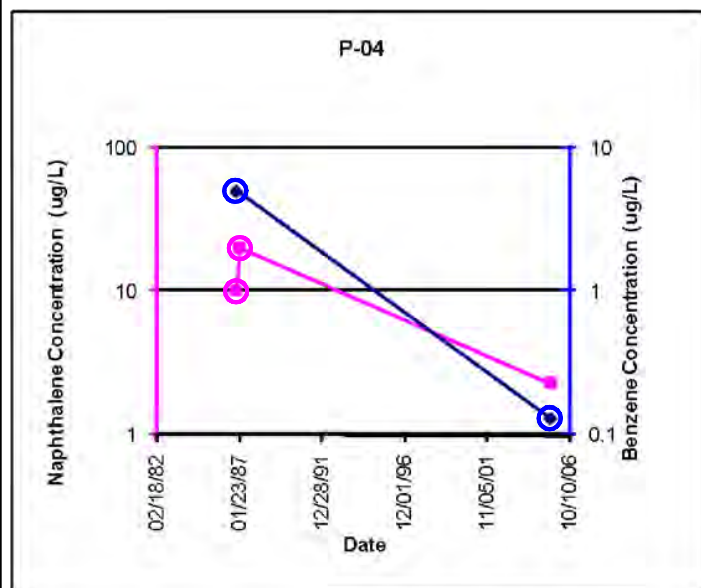
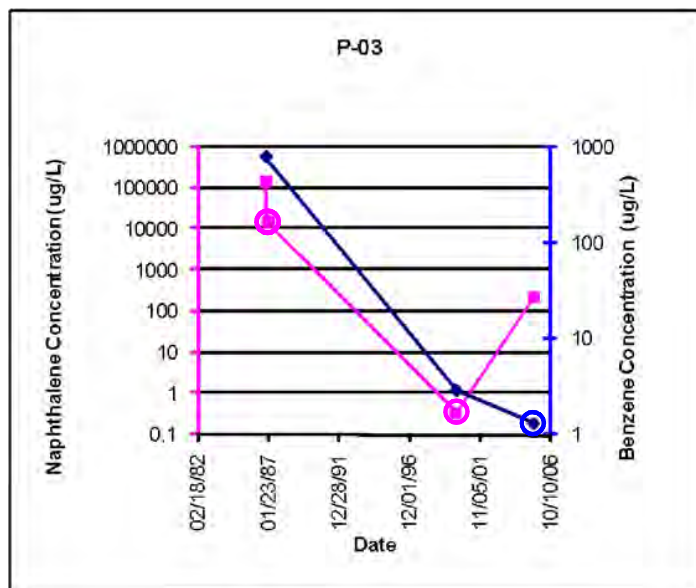
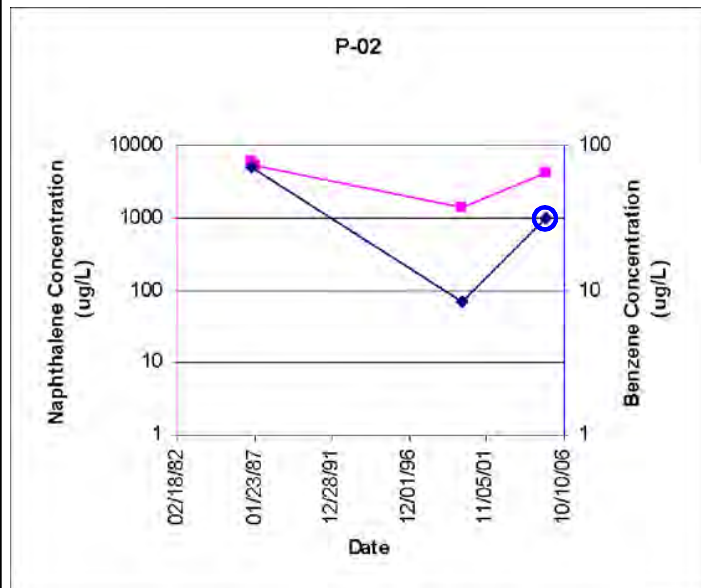
PROJECT NO: 11-233

FIGURE 4-5G

REFERENCE:

ISSUE DATE:

KEY ENVIRONMENTAL, INC.  
200 THIRD AVENUE  
CARNEGIE, PA 15106



### LEGEND

- NAPHTHALENE
- ◆ BENZENE
- (pink) NON-DETECT FOR NAPHTHALENE; VALUE REPRESENTS REPORTING LIMIT
- (blue) NON-DETECT FOR BENZENE; VALUE REPRESENTS REPORTING LIMIT

BEAZER EAST, INC.  
PITTSBURGH, PENNSYLVANIA

DRWN: TDD DATE: 02/11/11  
CHKD: RJH DATE: 02/11/11  
APPD: JSZ DATE: 02/11/11  
SCALE: NOT TO SCALE

**KEY** ENVIRONMENTAL  
INCORPORATED

NA TECHNICAL MEMORANDUM  
SOUTH CAVALCADE SUPERFUND SITE  
HOUSTON, TEXAS

TIME SERIES PLOTS OF  
NAPHTHALENE AND BENZENE

PROJECT NO: 11-233

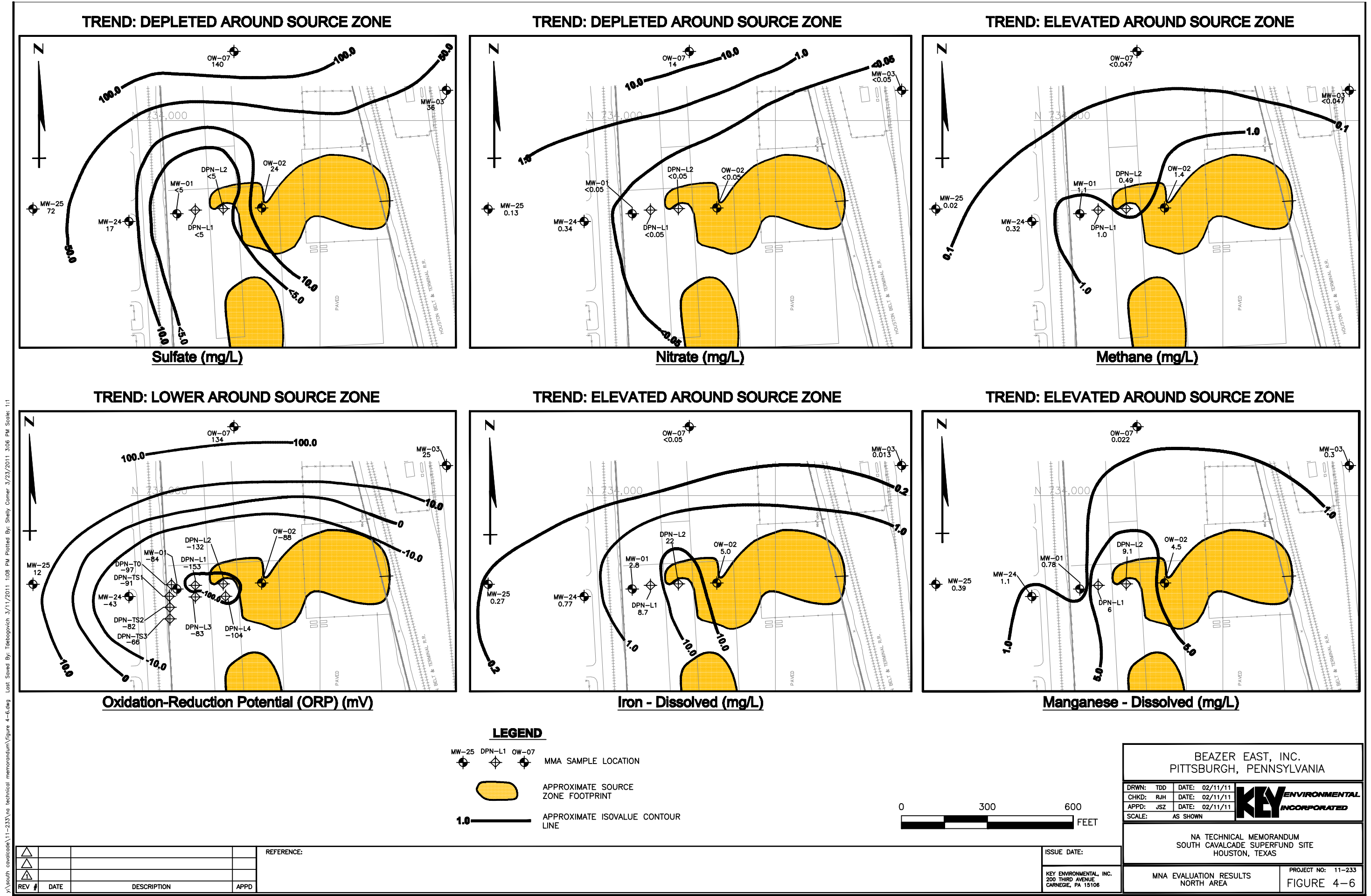
FIGURE 4-5H

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## ATTACHMENT 1

### SUMMARY OF LITERATURE BENZENE AND NAPHTHALENE DEGRADATION RATES

# ATTACHMENT 1

## SUMMARY OF LITERATURE BENZENE AND NAPHTHALENE DEGRADATION RATES

**Table A-1:** First order degradation rates (reported in half life days) of BTEX and naphthalene compounds under various conditions (Blum et al., 2009).

Parameter	Method Tracer Test <sup>(a)</sup>	Plume <sup>(b)</sup>	Columns <sup>(c)</sup>
Benzene	no (> 800)	no (> 800)	no (> 42)
Toluene	100 ± 40	120 ± 25	0.3 ± 0.1
Ethylbenzene	- (d)	230 ± 30	no (> 42)
p-xylene	225 ± 75	-	no (> 42)
m- & p-xylene	-	170 ± 10	-
o-xylene	-	125 ± 10	no (> 42)
1,3,5-trimethylbenzene	-	180	-
Naphthalene	33 ± 6	160 ± 20	-

a. Values of deuterated compounds from the tracer test.

b. Preliminary data obtained after modeling the whole contaminant plume.

c. Data for degradation within the laboratory columns (because of the maximum residence time of 325 h for water in the column and ± 10% maximum error on organic measurements, the lowest first order degradation rate which is possible to determine with this experiment is  $1.9 \times 10^{-7} \text{ s}^{-1}$ , corresponding to a half-life of 42 days; and

d. No degradation was observed; -the compound was not investigated.

**Table A-2:** First order degradation rates of BTEX and naphthalene compounds under various conditions (Thierrin et al., 1993). Summary of the first order degradation rate constants ( $\lambda_1$ - $\lambda_3$ ) including the biodegradation rate constants based on the stable carbon isotopes ( $\lambda_4$ ) and Michaelis-Menten parameters (MM) for various organic compounds using the centre line method.

Method	Eq.	Parameter (Units)	XYL <sup>(1)</sup>	BNZ	TOL	EB	NAP	2-MN	ACE
First Order Decay Models	(6)	$\lambda_1$ [d <sup>-1</sup> ]	0.0025 (-0.3)	0.0020 (-0.3)	0.0034 (0.5)	0.0021 (-0.7)	0.0038 (-0.5)	0.0048 (0.3)	0.0022 (-0.4)
	(7)	$\lambda_2$ [d <sup>-1</sup> ]	0.0012 (0.9)	0.0008 (-2.3)	0.0022 (0.0)	0.0009 (0.7)	0.0017 (0.7)	0.0029 (0.4)	0.0001 (-8.7)
	(8)	$\lambda_3$ [d <sup>-1</sup> ]	0.0021 (0.2)	0.0016 (-0.5)	0.0031 (0.1)	0.0017 (-0.9)	0.0036 (-0.6)	0.0049 (0.2)	0.0017 (02)
CSIA (Anoxic)	(13)	$\lambda_4$ [d <sup>-1</sup> ]	0.0019 (0.9)	-	-	-	0.0004 (-51.9)	-	-
CSIA (Oxic)	(13)	$\lambda_4$ [d <sup>-1</sup> ]	-	-	-	-	0.0027 (0.4)	-	-
MM	(10)	$K_{\max}$ (ug/L/d)	0.11 (0.9)	0.07 (-0.01)	0.45 (0.6)	0.15 (0.5)	12.17 (1.0)	1.65 (1.0)	0.50 (0.8)
		Mc (ug/L)	19.4	20.7	100.9	19.8	1129.3	217.6	90.6

1. Abbreviations are as follows:

XYL - o-Xylene  
BNZ - Benzene  
TOL - Toluene  
EBZ - Ethylbenzene

ACE - Acenaphthylene  
NAP - Naphthalene  
2MN - 2-Metylnaphthalene



**ATTACHMENT 1**  
**SUMMARY OF LITERATURE BENZENE AND NAPHTHALENE DEGRADATION RATES**

**Table A-3:** Summary table of first-order anaerobic biodegradation rate constants for BTEX compounds (Aronson and Howard, 1997).

Study Type	Benzene	Toluene	Ethylbenzene	o-Xylene	m-Xylene	p-Xylene
Range, all studies	0-0.071 <sup>ab</sup>	0-5.18	0-6.5	0-0.68	0-1.7	0-0.24
Mean, all studies	0.0046 n=113	0.37 n=150	0.13 n=94	0.030 n=93	0.068 n=86	0.031 n=55
Mean, laboratory studies	0.0059 n=66	0.12 n=64	0.059 n=44	0.024 n=49	0.062 n=41	0.043 n=26
Range, field/ <i>in situ</i> studies	0-0.038	0-0.30	0-0.15	0-0.21	0-0.32	0-0.057
Mean, field/ <i>in situ</i> studies	0.0036 n=41	0.059 11=46	0.015 11=37	0.025 <sup>c</sup> n=33	0.039 <sup>c</sup> n=34	0.014 <sup>c</sup> n=26
Range, NO <sub>3</sub> -reducing studies	0-0.045	0-5.18	0-6.5	0-0.68	0-1.7	0-0.24
Mean, NO <sub>3</sub> -reducing studies	0.0023 n=38	0.63 n=42	0.28 n=34	0.040 n=38	0.12 n=35	0.047 n=18
Range, Fe-reducing studies	0-0.024	0-0.087	0-0.0032	0-0.056	0-0.02	0-0.02
Mean, Fe-reducing studies	0.0035 n=11	0.021 n=10	0.0011 n=8	0.0078 n=8	0.0052 n=8	0.0050 n=8
Range, SO <sub>4</sub> -reducing studies	0-0.047	0.011-0.11	0-0.029	0-0.16	0.024-0.17	0.032-0.17
Mean, SO <sub>4</sub> -reducing studies	0.016 n=9	0.049 n=9	0.0098 n=7	0.065 n=5	0.091 n=4	0.079 n=3
Range, methanogenic studies	0-0.052	0-0.186	0-0.46	0-0.21	0-0.10	0-0.08
Mean, methanogenic studies	0.005 n=16	0.029 n=22	0.05 n=14	0.021 n=11	0.021 n=8	0.015 n=7

<sup>a</sup> First-order rate constants in units of days<sup>-1</sup>

<sup>b</sup> Studies reporting "biodegrades" or zero-order rate constants were assigned a value equal to the mean of the positive rate constant values.

<sup>c</sup> When only the papers in common for the 3 xylenes were examined, the mean field/*in situ* microcosm rate constant values for the xylenes were as follows: o-xylene=0.21/day, m-xylene=0.016/day, and p-xylene=0.015/day (calculated for the field and *in situ* microcosm studies only).

**Table A-4:** Summary table of first-order anaerobic biodegradation rate constants for naphthalene (Aronson and Howard, 1997).

Site Name	Redox Regime	Study Type	Initial Conc.	Time (days)	Rate Constant	Lag (days)	Reference
Denmark	Meth	Batch reactor, groundwater inoculum	200 mg COD/L		NB		Lyngkilde, J et al. (1992)
Denmark	NO <sub>3</sub>	Batch reactor, groundwater inoculum	200 mg COD/L		NB		Lyngkilde, J et al. (1992)
Lower Glatt Valley, Switzerland	NO <sub>3</sub>	Column	21790 ug/L	6	NB		Kuhn, EP et al. (1988)
Seal Beach, CA	Meth	Column	0.052 umol/g	570	NB		Haag, F et al. (1991)
Seal Beach, CA	Meth	Column	0.052 umol/g	68	NB		Haag, F et al. (1991)

**ATTACHMENT 1**  
**SUMMARY OF LITERATURE BENZENE AND NAPHTHALENE DEGRADATION RATES**

Site Name	Redox Regime	Study Type	Initial Conc.	Time (days)	Rate Constant	Lag (days)	Reference
Gas Works Park Seattle, WA		Field	160 ug/L				Turney, GL & Georlitz, DF (1990)
North Bay landfill Ontario, Canada	Meth	Field	150 ug/L				Reinhard.M et al. (1984)
Pensacola, FL	Meth	Field	600-15600 ug/L	200-600			Goerlitz.DF et al. (1985)
Conroe, TX		Field	649.3 ug/L	15000	.000181/day		Bedient.PB et al. (1984)
Conroe, TX		Field	650-1600 ug/L	2963	0.0015-0.0021/day		Wilson.JT et al. (1985)
Noordwijk landfill, The Netherlands		Field	30 ug/L	3650	0.0063/day		Zoeteman,BCJ et al. (1981)
Swan Coastal Plain, Western Australia	SO <sub>4</sub> /Fe	Field	1200 ug/L	71	0.017-0.043/day		Thierriu,J et al. (199'5)
Vejen city landfill, Denmark	Meth/SO <sub>4</sub> /Fe	Field	24 ug/L	71	0.026/day		Lyngkilde,J & Christensen.,T H (1992)
		Field			Possible		EPRI (1993)
Conroe, TX		Field		4-6	Biodegrades		Borden,RC & Bedient,PB (1987)
Santa Clara Valley, CA		Field	0.91 ug/L	0.5	Biodegrades		Roberts,PV et al. (1980)
Pensacola. FL	Meth	Field	9380 ug/L	150	NB		Godsy,EM et al. (1992)
Upstate New York		Field		21	NB		Madsen,L et al. (1996)
Grindsted landfill, Denmark	Meth/SO <sub>4</sub> /Fe	Field	190 ug/L	21	Possible		Rugge,K et al. (1995)
St. Louis Park, MN	Meth	Field	15500 ug/L		Possible		Ehrlich,GG et al (1982)
Conroe, TX		Groundwater grab sample			0.307/day		Ward,CH et al. (1986)
Florida		Groundwater grab sample		90	NB		Delfino,JJ et al. (1989)
Fredensborg, Denmark	NO <sub>3</sub>	Groundwater grab sample	500 ug/L	200	NB		Elyvbjerg,J et al. (1993)
Fredensborg, Denmark	NO <sub>3</sub>	Groundwater grab sample	500 ug/L	60	NB		Elyvbjerg,J et al. (1993)
Fredensborg, Denmark	SO <sub>4</sub>	Groundwater grab sample	500 ug/L	235	NB		Elyvbjerg,J et al. (1993)
New York		Groundwater grab sample	500-1000 ug/L	6	NB		Madsen,EL et al (1991)
New York		Groundwater grab sample	500-1000	6	Possible		Madsen,EL et al (1991)

**ATTACHMENT 1**  
**SUMMARY OF LITERATURE BENZENE AND NAPHTHALENE DEGRADATION RATES**

Site Name	Redox Regime	Study Type	Initial Conc.	Time (days)	Rate Constant	Lag (days)	Reference
			ug/L				
Vejen city landfill, Denmark	Fe	In situ microcosm	75 ug/L	48	0.0050/day		Nielsen,PH & Christensen,T H (1994)
North Bay landfill Ontario, Canada	Meth/SO <sub>4</sub>	In situ microcosm	150 ug/L	78	Biodegrades		Acton,DW & Barker,JF (1992)
Vejen city landfill, Denmark	Meth	In situ microcosm	150 ug/L	90	NB		Nielsen,PH et al (1992)
Vejen city landfill, Denmark	Meth	In situ microcosm	120 ug/L	94	NB		Nielsen,PH & Christensen,T H (1994)
Vejen city landfill, Denmark	Meth/Fe/NO <sub>3</sub>	In situ microcosm	150 ug/L	90-180	NB		Nielsen,PH et al. (1997)
Vejen city landfill, Denmark	NO <sub>3</sub>	In situ microcosm	150 ug/L	80	NB		Nielsen,PH & Christensen,T H (1994)
Pensacola, FL	Meth	Lab microcosm	10000 ug/L	112	0.0057/day		Sharak-Genthner,BR et al. (1997)
Conroe, TX		Lab microcosm		21	Biodegrades		Thomas,JM et al. (1989)
Conroe, TX		Lab microcosm		8	Biodegrades		Thomas,JM et al. (1989)
Bemidji, MN	Meth/Fe/Mn	Lab microcosm	1282 ug/L	45	NB		Baedecker,MJ et al. (1993)
Cliff-Dow Chemical Co Marquette, MI		Lab microcosm	500 ug/L	84	NB		Klecka,GM et al. (1990A)
North Bay landfill, Ontario, Canada		Lab microcosm	131.8 ug/L	187	NB		Acton,DW & Barker,JF (1992)
North Bay landfill, Ontario, Canada	NO <sub>3</sub>	Lab microcosm	148.5 ug/L	181	NB		Acton,DW & Barker,JF (1992)
Pensacola, FL	Meth/NO <sub>3</sub> /SO <sub>4</sub>	Lab microcosm	58300 ug/L	365	NB		Sharak-Genthner,BR et al. (1997)

**Table A-5:** Napthalene half-lives in ground-water (Howard et al., 1997)

Parameter	Matrix	Half life (days)	
		Low	High
Naphthalene	Ground-water	1	258

Scientific judgment based on estimated unacclimated aerobic (low t<sub>1/2</sub>) and anaerobic (high t<sub>1/2</sub>) biodegradation half-lives.

ATTACHMENT 2

DATA SET FOR MASS BUDGETING AND ASSIMILATIVE CAPACITY ANALYSIS



**ATTACHMENT 2**  
**ASSIMILATION CAPACITY ASSESSMENT DATA**  
**NATURAL ATTENUATION PARAMETERS AND CONSTITUENTS OF INTEREST**

Well	Date	Parameter	Result		Units
North Area - Upgradient - NA Parameters					
MW-03	12/13/99	Alkalinity (as CaCO3)	470		mg/l
MW-03	12/13/99	Ammonia (as N)	0.05		mg/l
MW-03	12/13/99	BOD	8.1		mg/l
MW-03	12/13/99	Carbon Dioxide	12		mg/l
MW-03	12/13/99	Chloride	29		mg/l
MW-03	12/13/99	COD	20	U	mg/l
MW-03	12/13/99	Iron (Dissolved)	0.013	B	mg/l
MW-03	12/13/99	Manganese (Dissolved)	0.3		mg/l
MW-03	12/13/99	Methane	0.047	U	mg/l
MW-03	12/13/99	Nitrate	0.05	U	mg/l
MW-03	12/13/99	Orthophosphate	0.16		mg/l
MW-03	12/13/99	Sulfate	36		mg/l
MW-03	12/13/99	TOC	5.6		mg/l
North Area - Upgradient - Constituents of Interest					
MW-03	12/13/99	Benzene	1	U	ug/l
MW-03	12/13/99	o-Xylene	1	U	ug/l
MW-03	12/13/99	Ethylbenzene	1	U	ug/l
MW-03	12/13/99	Toluene	1	U	ug/l
MW-03	12/13/99	m/p-xylene	1	U	ug/l
MW-03	12/13/99	Naphthalene	20		ug/l
Total BTEX and Naphthalene <sup>(1)</sup>			0.025		mg/L
North Area - Source Area - NA Parameters					
OW-02	12/14/99	Alkalinity (as CaCO3)	410		mg/l
OW-02	12/14/99	Ammonia (as N)	0.19		mg/l
OW-02	12/14/99	BOD	32		mg/l
OW-02	12/14/99	Carbon Dioxide	110	D	mg/l
OW-02	12/14/99	Chloride	14		mg/l
OW-02	12/14/99	COD	120		mg/l
OW-02	12/14/99	Iron (Dissolved)	5		mg/l
OW-02	12/14/99	Manganese (Dissolved)	4.5		mg/l
OW-02	12/14/99	Methane	1.4	D	mg/l
OW-02	12/14/99	Nitrate	0.05	U	mg/l
OW-02	12/14/99	Orthophosphate	0.17		mg/l
OW-02	12/14/99	Sulfate	24		mg/l
OW-02	12/14/99	TOC	49		mg/l
North Area - Source Area - Constituents of Interest					
OW-02	12/14/99	Benzene	16		ug/l
OW-02	12/14/99	o-Xylene	45		ug/l
OW-02	12/14/99	Ethylbenzene	35		ug/l
OW-02	12/14/99	Toluene	49		ug/l
OW-02	12/14/99	m/p-xylene	82		ug/l
OW-02	12/14/99	Naphthalene	11000	D	ug/l
Total BTEX and Naphthalene <sup>(1)</sup>			11.227		mg/L
North Area - Downgradient - NA Parameters					
MW-01	04/11/00	Alkalinity (as CaCO3)	460		mg/l
MW-01	04/11/00	Ammonia (as N)	0.03	U	mg/l
MW-01	04/11/00	BOD	2	U	mg/l
MW-01	04/11/00	Carbon Dioxide	61	EB	mg/l
MW-01	04/11/00	Chloride	68		mg/l
MW-01	04/11/00	COD	20	U	mg/l
MW-01	04/11/00	Iron (Dissolved)	2.8		mg/l
MW-01	04/11/00	Manganese (Dissolved)	0.48		mg/l
MW-01	04/11/00	Methane	1.1		mg/l
MW-01	04/11/00	Nitrate	0.05	U	mg/l
MW-01	04/11/00	Orthophosphate	0.23		mg/l
MW-01	04/11/00	Sulfate	5	U	mg/l
MW-01	04/11/00	TOC	6		mg/l
North Area - Downgradient - Constituents of Interest					
MW-01	04/11/00	Benzene	4.1		ug/l
MW-01	04/11/00	o-Xylene	6.9		ug/l
MW-01	04/11/00	Ethylbenzene	8		ug/l
MW-01	04/11/00	Toluene	5.7		ug/l
MW-01	04/11/00	m/p-xylene	14		ug/l
MW-01	04/11/00	Naphthalene	340		ug/l
Total BTEX and Naphthalene <sup>(1)</sup>			0.3787		mg/L

**ATTACHMENT 2**  
**ASSIMILATION CAPACITY ASSESSMENT DATA**  
**NATURAL ATTENUATION PARAMETERS AND CONSTITUENTS OF INTEREST**

Well	Date	Parameter	Result	Units
<b>South Area - Upgradient - NA Parameters</b>				
MW-07	12/14/99	Alkalinity (as CaCO <sub>3</sub> )	250	mg/l
MW-07	12/14/99	Ammonia (as N)	0.11	mg/l
MW-07	12/14/99	BOD	2	U mg/l
MW-07	12/14/99	Carbon Dioxide	9.7	mg/l
MW-07	12/14/99	Chloride	5.5	mg/l
MW-07	12/14/99	COD	20	U mg/l
MW-07	12/14/99	Iron (Dissolved)	0.7	mg/l
MW-07	12/14/99	Manganese (Dissolved)	3.2	mg/l
MW-07	12/14/99	Methane	0.047	U mg/l
MW-07	12/14/99	Nitrate	0.05	U mg/l
MW-07	12/14/99	Orthophosphate	0.1	mg/l
MW-07	12/14/99	Sulfate	61	mg/l
MW-07	12/14/99	TOC	8.3	mg/l
<b>South Area - Upgradient - Constituents of Interest</b>				
MW-07	12/14/99	Benzene	1	U ug/l
MW-07	12/14/99	o-Xylene	1	U ug/l
MW-07	12/14/99	Ethylbenzene	1	U ug/l
MW-07	12/14/99	Toluene	1	U ug/l
MW-07	12/14/99	m/p-xylene	1	U ug/l
MW-07	12/14/99	Naphthalene	0.72	J ug/l
<b>Total BTEX and Naphthalene <sup>(1)</sup></b>			0.00572	mg/L
<b>South Area - Source Area - NA Parameters</b>				
OW-10	12/13/99	Alkalinity (as CaCO <sub>3</sub> )	410	mg/l
OW-10	12/13/99	Ammonia (as N)	0.04	mg/l
OW-10	12/13/99	BOD	45	mg/l
OW-10	12/13/99	Carbon Dioxide	17	mg/l
OW-10	12/13/99	Chloride	49	mg/l
OW-10	12/13/99	COD	160	mg/l
OW-10	12/13/99	Iron (Dissolved)	1.3	mg/l
OW-10	12/13/99	Manganese (Dissolved)	1.1	mg/l
OW-10	12/13/99	Methane	0.17	mg/l
OW-10	12/13/99	Nitrate	0.05	U mg/l
OW-10	12/13/99	Orthophosphate	0.18	mg/l
OW-10	12/13/99	Sulfate	5	U mg/l
OW-10	12/13/99	TOC	42	mg/l
<b>South Area - Source Area - Constituents of Interest</b>				
OW-10	12/13/99	Benzene	650	ug/l
OW-10	12/13/99	o-Xylene	300	ug/l
OW-10	12/13/99	Ethylbenzene	260	ug/l
OW-10	12/13/99	Toluene	660	ug/l
OW-10	12/13/99	m/p-xylene	650	ug/l
OW-10	12/13/99	Naphthalene	26000	E ug/l
<b>Total BTEX and Naphthalene <sup>(1)</sup></b>			28.52	mg/L
<b>South Area - Downgradient - NA Parameters</b>				
MW-26	04/11/00	Alkalinity (as CaCO <sub>3</sub> )	450	mg/l
MW-26	04/11/00	Ammonia (as N)	0.03	U mg/l
MW-26	04/11/00	BOD	2.8	mg/l
MW-26	04/11/00	Carbon Dioxide	34	mg/l
MW-26	04/11/00	Chloride	37	mg/l
MW-26	04/11/00	COD	20	U mg/l
MW-26	04/11/00	Iron (Dissolved)	1.5	mg/l
MW-26	04/11/00	Manganese (Dissolved)	0.58	mg/l
MW-26	04/11/00	Methane	0.022	mg/l
MW-26	04/11/00	Nitrate	0.05	U mg/l
MW-26	04/11/00	Orthophosphate	0.086	mg/l
MW-26	04/11/00	Sulfate	38	mg/l
MW-26	04/11/00	TOC	5.8	mg/l
<b>South Area - Downgradient - Constituents of Interest</b>				
MW-26	04/17/00	Benzene	500	U ug/l
MW-26	04/17/00	o-Xylene	500	U ug/l
MW-26	04/17/00	Ethylbenzene	500	U ug/l
MW-26	04/17/00	Toluene	500	U ug/l
MW-26	04/17/00	m/p-xylene	500	U ug/l
MW-26	04/17/00	Naphthalene	2100	E ug/l
<b>Total BTEX and Naphthalene <sup>(1)</sup></b>			4.6	mg/L

1. Reporting limits used as input for calculation of total COI concentration for nondetects.

**ATTACHMENT 2**  
**ASSIMILATION CAPACITY ASSESSMENT DATA**  
**FIELD PARAMETERS**

<i>Sample Location</i>	<i>Temperature (° C)</i>	<i>pH (S.U.)</i>	<i>Specific Conductivity (mS/m)</i>	<i>ORP (mV)</i>	<i>Turbidity (NTU)</i>	<i>D.O. Probe (mg/L)</i>	<i>D.O. Ampoule (mg/L)</i>
<i>North Area</i>							
MW-03	22.98	6.4	110	25	2	0.4	0.2
OW-02	24.08	6.3	85	-88	-10*	0.4	0.6
MW-01	21.7	6.7	0.1	-84	250	6.55	0.8
<i>South Area</i>							
MW-07	25.0	6.79	55.0	-80	18	0.45	0.4
OW-10	24.40	6.7	75	-77	590	2.1	2.0
MW-26	23.8	6.8	0.11	105	-10	4.37	4.0

1. Table 4-3 from VGFTER parsed and organized to display shallow zone dissolved oxygen results for north and south are  
MW-01 DO probe results considered suspect. Upgradient dissolved oxygen depleted (upgradient aerobic respiratio

ATTACHMENT 3

MASS BUDGETING AND ASSIMILATIVE CAPACITY CALCULATION SPREADSHEETS



### ATTACHMENT 3

Mass Budgeting Analysis and Assimilative Capacity Calculations  
Shallow Aquifer Zone - North Area

South Cavalcade Superfund Site  
Houston, Texas

**Objective:** Determine theoretical mass assimilation capacities for naphthalene and benzene based on measured NA parameter concentrations.  
Assimilation capacities in terms of mass/L and total mass (lbs) per year, based on groundwater flux will be determined.

**Representative Field Measurements:**

Well Identification	Well Location	Sampling Date	Concentrations (mg/L) <sup>(1)</sup>						
			Reactants				Products		
			DO	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	COIs	CH <sub>4</sub>	Fe <sup>2+</sup>	CO <sub>2</sub>
MW-03	Upgradient	12/13/99	0.400	0.025	36	0.0205	0.047	0.01	12
OW-02	Source	12/14/99	0.200	0.025	24	9.714	1.40	5.00	110
MW-01	Downgradient	04/11/00	0.800	0.025	2.5	0.3441	1.1	2.80	61
Values at maximum NA <sup>(2)</sup>			0.200	0.025	2.5	0.3441	1.40	5.00	110
Values at minimum NA <sup>(2)</sup>			0.800	0.025	24	9.714	1.1	2.80	61
Average NA			0.5	0.025	13.25	5.02905	1.25	3.9	85.5

- Analytical results for NA parameters and COIs (benzene and naphthalene) summarized in attached data tables from data base and historical investigation reports.
- Maximum NA indication values are the minima of the source/downgradient well values for reactants and the maxima of the source/downgradient well values for products.  
Minimum NA indication values are the maxima of the source/downgradient well values for reactants and the minima of the source/downgradient well values for products.

**COI and Geochemical Indicator Differences:**

Natural Attenuation Indicator Parameter	Upgradient (mg/L)	Downgradient (mg/L)			Difference (mg/L)		
		Max NA	Min NA	Average	Max NA	Min NA	Average
Dissolved Oxygen (DO)	0.400	0.200	0.800	0.5	-0.200	0.400	0.100
Nitrate as Nitrogen (NO <sub>3</sub> <sup>-</sup> )	0.025	0.025	0.025	0.025	0.000	0.000	0.000
Sulfate as Sulfur (SO <sub>4</sub> <sup>2-</sup> )	36	2.5	24	13.25	-33.500	-12.000	-22.750
Benzene and Naphthalene (COIs)	0.0205	0.3441	9.714	5.029	0.324	9.694	5.009
Methane (CH <sub>4</sub> )	0.047	1.40	1.1	1.25	1.353	1.053	1.203
Ferrous Iron (Fe <sup>2+</sup> )	0.01	5.00	2.80	3.9	4.987	2.787	3.887
Dissolved Inorganic Carbon (CO <sub>2</sub> )	12	110	61	85.5	98.000	49.000	73.500

**Literature Stoichiometric Ratios:**

Biological Process	g COI/g Acceptor	g CO <sub>2</sub> -C/g Acceptor	g Alkalinity/g Acceptor
Aerobic Respiration (O <sub>2</sub> reactant)	0.319	-0.29	0
Denitrification (NO <sub>3</sub> <sup>-</sup> reactant)	0.917	-0.83	-3.57
Sulfate Reduction (SO <sub>4</sub> <sup>2-</sup> reactant)	0.637	-0.53	-3.13
Methanogenesis (CH <sub>4</sub> product)	-1.28	0.42	0
Iron Reduction (Fe <sup>2+</sup> product)	-0.046	0.042	1.79

### Assimilation Capacity Calculations (COIs):

Biological Process	Observed Changes			Computed Changes - COIs		
	Max NA	Min NA	Average	Max NA	Min NA	Average
Aerobic Respiration (O <sub>2</sub> reactant)	-0.200	0.400	0.100	-0.064	0.128	0.032
Denitrification (NO <sub>3</sub> <sup>-</sup> reactant)	0.000	0.000	0.0000	0.000	0.000	0.0000
Sulfate Reduction (SO <sub>4</sub> <sup>2-</sup> reactant)	-33.50	-12.00	-22.75	-21.340	-7.644	-14.492
Methanogenesis (CH <sub>4</sub> product)	1.353	1.053	1.203	-1.732	-1.348	-1.540
Iron Reduction (Fe <sup>2+</sup> product)	4.987	2.787	3.887	-0.229	-0.128	-0.179
<b>Total</b>				<b>23.4</b>	<b>9.0</b>	<b>16.2</b>

### Assimilation Capacity Calculations (CO<sub>2</sub>):

Biological Process	Observed Changes			Computed Changes - CO <sub>2</sub>		
	Max NA	Min NA	Average	Max NA	Min NA	Average
Aerobic Respiration (O <sub>2</sub> reactant)	-0.200	0.400	0.100	0.058	-0.116	-0.029
Denitrification (NO <sub>3</sub> <sup>-</sup> reactant)	0.000	0.000	0.000	0.000	0.000	0.000
Sulfate Reduction (SO <sub>4</sub> <sup>2-</sup> reactant)	-33.500	-12.000	-22.750	17.755	6.360	12.058
Methanogenesis (CH <sub>4</sub> product)	1.353	1.053	1.203	0.568	0.442	0.505
Iron Reduction (Fe <sup>2+</sup> product)	4.987	2.787	3.887	0.209	0.117	0.163
<b>Total</b>				<b>18.6</b>	<b>6.8</b>	<b>12.7</b>

### Assimilation Capacity Calculations (Alkalinity):

Biological Process	Observed Changes			Computed Changes - Alkalinity		
	Max NA	Min NA	Average	Max NA	Min NA	Average
Aerobic Respiration (O <sub>2</sub> reactant)	-0.200	0.400	0.100	0.000	0.000	0.000
Denitrification (NO <sub>3</sub> <sup>-</sup> reactant)	0.000	0.000	0.000	0.000	0.000	0.000
Sulfate Reduction (SO <sub>4</sub> <sup>2-</sup> reactant)	-33.500	-12.000	-22.750	104.855	37.560	71.208
Methanogenesis (CH <sub>4</sub> product)	1.353	1.053	1.203	0.000	0.000	0.000
Iron Reduction (Fe <sup>2+</sup> product)	4.987	2.787	3.887	8.927	4.989	6.958
<b>Total</b>				<b>113.8</b>	<b>42.5</b>	<b>78.2</b>

### Groundwater Flux:

Hydraulic Conductivity	22.1	ft/day
Hydraulic Gradient	2.00E-03	ft/ft
Plume Width	250	ft
Plume Thickness	10	ft
Darcy Flux	110.5	ft <sup>3</sup> /day
Darcy Flux	1.14E+06	L/yr

### Mass Assimilated/Year:

Determined as Groundwater Flux (L/yr) x Computed Change in COI Conc.  
(e.g., Max = (1.14x10<sup>6</sup> L/yr) x (23.4 mg/L) x (0.001 g/mg) x (1 lb/454 g)

Maximum Nat. Attenuation:	58.8	lbs COI/yr
Minimum Nat. Attenuation:	22.6	lbs COI/yr
Average Nat. Attenuation:	40.7	lbs COI/yr

1. Supporting information from historical reports is attached (concentration data and hydraulic information for the north and south areas).

### ATTACHMENT 3

Mass Budgeting Analysis and Assimilative Capacity Calculations  
Shallow Aquifer Zone - South Area

South Cavalcade Superfund Site  
Houston, Texas

**Objective:** Determine theoretical mass assimilation capacities for naphthalene and benzene based on measured NA parameter concentrations.  
Assimilation capacities in terms of mass/L and total mass (lbs) per year, based on groundwater flux will be determined.

**Representative Field Measurements:**

Well Identification	Well Location	Sampling Date	Concentrations (mg/L) <sup>(1)</sup>						
			Reactants				Products		
			DO	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	COIs	CH <sub>4</sub>	Fe <sup>2+</sup>	CO <sub>2</sub>
MW-07	Upgradient	12/14/99	0.400	0.025	61	0.0057	0.0235	0.70	9.7
OW-10	Source	12/13/99	2.000	0.025	2.5	28.52	0.17	1.30	17
MW-26	Downgradient	04/11/00	4.000	0.015	38	4.6	0.022	1.50	34
Values at maximum NA <sup>(2)</sup>			2.000	0.015	2.5	4.6	0.17	1.50	34
Values at minimum NA <sup>(2)</sup>			4.000	0.025	38	28.52	0.022	1.30	17
Average NA			3	0.02	20.25	16.56	0.096	1.4	25.5

- Analytical results for NA parameters and COIs (benzene and naphthalene) summarized in attached data tables from data base and historical investigation reports.
- Maximum NA indication values are the minima of the source/downgradient well values for reactants and the maxima of the source/downgradient well values for products.  
Minimum NA indication values are the maxima of the source/downgradient well values for reactants and the minima of the source/downgradient well values for products.

**COI and Geochemical Indicator Differences:**

Natural Attenuation Indicator Parameter	Upgradient (mg/L)	Downgradient (mg/L)			Difference (mg/L)		
		Max NA	Min NA	Average	Max NA	Min NA	Average
Dissolved Oxygen (DO)	0.400	2.000	4.000	3	1.600	3.600	2.600
Nitrate as Nitrogen (NO <sub>3</sub> <sup>-</sup> )	0.025	0.015	0.025	0.02	-0.010	0.000	-0.005
Sulfate as Sulfur (SO <sub>4</sub> <sup>2-</sup> )	61	2.5	38	20.25	-58.500	-23.000	-40.750
Benzene and Naphthalene (COIs)	0.0057	4.6	28.52	16.560	4.594	28.514	16.554
Methane (CH <sub>4</sub> )	0.0235	0.17	0.022	0.096	0.147	-0.002	0.073
Ferrous Iron (Fe <sup>2+</sup> )	0.70	1.50	1.30	1.4	0.800	0.600	0.700
Dissolved Inorganic Carbon (CO <sub>2</sub> )	9.7	34	17	25.5	24.300	7.300	15.800

**Literature Stoichiometric Ratios:**

Biological Process	g COI/g Acceptor	g CO <sub>2</sub> -C/g Acceptor	g Alkalinity/g Acceptor
Aerobic Respiration (O <sub>2</sub> reactant)	0.319	-0.29	0
Denitrification (NO <sub>3</sub> <sup>-</sup> reactant)	0.917	-0.83	-3.57
Sulfate Reduction (SO <sub>4</sub> <sup>2-</sup> reactant)	0.637	-0.53	-3.13
Methanogenesis (CH <sub>4</sub> product)	-1.28	0.42	0
Iron Reduction (Fe <sup>2+</sup> product)	-0.046	0.042	1.79

### Assimilation Capacity Calculations (COIs):

Biological Process	Observed Changes			Computed Changes - COIs		
	Max NA	Min NA	Average	Max NA	Min NA	Average
Aerobic Respiration (O <sub>2</sub> reactant)	1.600	3.600	2.600	0.510	1.148	0.829
Denitrification (NO <sub>3</sub> <sup>-</sup> reactant)	-0.010	0.000	-0.0050	-0.009	0.000	-0.0046
Sulfate Reduction (SO <sub>4</sub> <sup>2-</sup> reactant)	-58.50	-23.00	-40.75	-37.265	-14.651	-25.958
Methanogenesis (CH <sub>4</sub> product)	0.147	-0.002	0.073	-0.188	0.002	-0.093
Iron Reduction (Fe <sup>2+</sup> product)	0.800	0.600	0.700	-0.037	-0.028	-0.032
<b>Total</b>				<b>37.0</b>	<b>13.5</b>	<b>25.3</b>

### Assimilation Capacity Calculations (CO<sub>2</sub>):

Biological Process	Observed Changes			Computed Changes - CO <sub>2</sub>		
	Max NA	Min NA	Average	Max NA	Min NA	Average
Aerobic Respiration (O <sub>2</sub> reactant)	1.600	3.600	2.600	-0.464	-1.044	-0.754
Denitrification (NO <sub>3</sub> <sup>-</sup> reactant)	-0.010	0.000	-0.005	0.008	0.000	0.004
Sulfate Reduction (SO <sub>4</sub> <sup>2-</sup> reactant)	-58.500	-23.000	-40.750	31.005	12.190	21.598
Methanogenesis (CH <sub>4</sub> product)	0.147	-0.002	0.073	0.062	-0.001	0.030
Iron Reduction (Fe <sup>2+</sup> product)	0.800	0.600	0.700	0.034	0.025	0.029
<b>Total</b>				<b>30.6</b>	<b>11.2</b>	<b>20.9</b>

### Assimilation Capacity Calculations (Alkalinity):

Biological Process	Observed Changes			Computed Changes - Alkalinity		
	Max NA	Min NA	Average	Max NA	Min NA	Average
Aerobic Respiration (O <sub>2</sub> reactant)	1.600	3.600	2.600	0.000	0.000	0.000
Denitrification (NO <sub>3</sub> <sup>-</sup> reactant)	-0.010	0.000	-0.005	0.036	0.000	0.018
Sulfate Reduction (SO <sub>4</sub> <sup>2-</sup> reactant)	-58.500	-23.000	-40.750	183.105	71.990	127.548
Methanogenesis (CH <sub>4</sub> product)	0.147	-0.002	0.073	0.000	0.000	0.000
Iron Reduction (Fe <sup>2+</sup> product)	0.800	0.600	0.700	1.432	1.074	1.253
<b>Total</b>				<b>184.6</b>	<b>73.1</b>	<b>128.8</b>

### Groundwater Flux:

Hydraulic Conductivity	4.35	ft/day
Hydraulic Gradient	3.00E-03	ft/ft
Plume Width	420	ft
Plume Thickness	10	ft
Darcy Flux	54.81	ft <sup>3</sup> /day
Darcy Flux	5.66E+05	L/yr

### Mass Assimilated/Year:

Determined as Groundwater Flux (L/yr) x Computed Change in COI Conc.  
(e.g., Max = (1.14x10<sup>6</sup> L/yr) x (23.4 mg/L) x (0.001 g/mg) x (1 lb/454 g)

Maximum Nat. Attenuation:	46.2	lbs COI/yr
Minimum Nat. Attenuation:	16.9	lbs COI/yr
Average Nat. Attenuation:	31.5	lbs COI/yr

1. Supporting information from historical reports is attached (concentration data and hydraulic information for the north and south areas).



### Attachment 3 Supporting Information

**Except from Groundwater Fate and Transport Evaluation Report Section 2.1.4 – Hydrogeologic Conditions (Key Environmental, Inc., August 1997). References and figures excluded:**

*“Groundwater flow in the shallow aquifer is to the west. Observed horizontal hydraulic gradients range from 0.002 ft/ft to 0.006 ft/ft in the Northern Area and 0.003 to 0.006 ft/ft in the Southern Area (Keystone, July 1988). A potentiometric surface contour map for the shallow aquifer constructed from elevation data presented in the RI Report is included as Figure 7. Hydraulic conductivities have been determined through the completion of aquifer testing programs conducted in the southern and northern portions of the Site. An average hydraulic conductivity of  $7.8 \times 10^{-3}$  cm/sec (8,070 ft/year) for the shallow aquifer in the northern portion of the Site (i.e., GRAA 1) was determined from data obtained from a constant rate pumping test performed during the Groundwater Collection Trench Pilot Study. An average hydraulic conductivity value of  $1.6 \times 10^{-3}$  cm/sec (1,655 ft/year) was calculated for the shallow aquifer in the southwestern portion of the Site (i.e., GRAA 3) from data obtained through a constant rate pumping test performed as part of the Extraction Well Pilot Study.*

*Average hydraulic conductivities for the discontinuous silty sand unit within the intermediate aquitard in the northern (i.e., GRAA 1) and southwestern (i.e., GRAA 3) portions of the Site were estimated as  $3.9 \times 10^{-4}$  cm/sec (404 ft/year) and  $3.2 \times 10^{-4}$  cm/sec (331 ft/year) respectively. These data were obtained from constant rate pumping tests conducted as part of the Extraction Well Pilot Study. These estimated average hydraulic conductivity values for the discontinuous silty sand zone within the intermediate aquitard are approximately one order of magnitude less than the hydraulic conductivities estimated for the shallow aquifer.”*

ATTACHMENT 4  
SUMMARY OF PLFA RESULTS

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## MICROBIAL ANALYSIS SUMMARY REPORT

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**Client:** Jim Zubrow  
Key Environmental  
1200 Arch St.  
Carnegie, PA 15106

**Phone:** (412) 279-3363  
**Fax:** (412) 279-4332

**MI Identifier:** 1Key

**Analysis Performed:** PLFA Analysis

**Date Received:** 12/8-9/99

**Project:** Beazer South Cavalcade

**Report Date:** 1/14/00

**Project No.:** 99-785

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### SUMMARY OF RESULTS

At these sites:

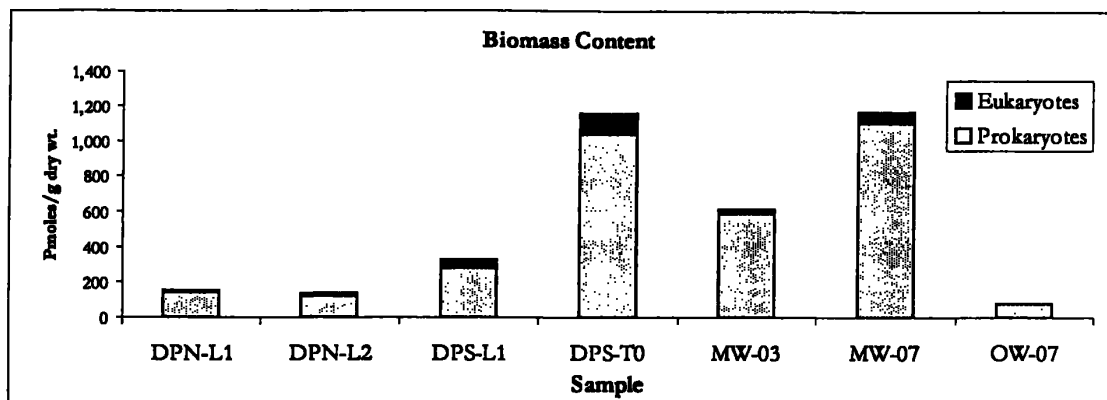
- Biomass content was lowest in the control sample (OW-07), and highest in samples MW-07 and DPS-T0.
- OW-07 contained a different microbial community (predominantly *Actinomyces*) than did the remaining samples.
- Microbes in the remaining samples were predominantly Gram negative, with relatively high proportions of anaerobic sulfate/metal reducing bacteria.
- Bacteria in DPN-L2 and DPS-L1 demonstrated a physiological response to the contaminants.

### RESULTS AND DISCUSSION

#### BIOMASS

Phospholipid fatty acids (PLFA) are found within the membranes of all living cells but decompose quickly upon cell death. Thus, measuring PLFA content provides a quantitative measure of the viable microbial biomass present (1-2).

**Microbial Insights, Inc.**  
2340 Stock Creek Blvd. Rockford TN 37853-3044  
Phone: (423) 573-8188 Fax: (423) 573-8133



**Figure 1.** Biomass content.

Biomass content was lowest in sample OW-07 and highest in samples MW-07 and DPS-T0 (Figure 1).

#### COMMUNITY COMPOSITION

To relate the complex mixture of PLFA to the organisms present, a structural group interpretation is employed (3-5). In some cases these associations are so strong that fatty acid biomarkers have been identified for particular organisms.

**Table 1.** PLFA Structure Groups.

PLFA Structural Group	General classification
Monoenoics (Monos)	Found in Gram negative bacteria, which are fast growing, utilize many carbon sources, and adapt quickly to a variety of environments.
Terminally Branched Saturated (TerBrSats)	Representative of Gram positive bacteria, but may also be found in the cell membranes of some Gram negative bacteria.
Branched Monoenoic (BrMonos)	Commonly found in the cell membranes of obligate anaerobes such as sulfate or iron reducing bacteria
Mid-Chain Branched Saturated (MidBrSats)	Common in Actinomycete, sulfate reducing bacteria and certain Gram positive bacteria.
Normal Saturated (Nsats)	Found in both the prokaryotic and eukaryotic kingdoms.
Eukaryotes	Found in organisms such as fungi, protozoa, algae, higher plants and animals.

Comparison of the PLFA profiles showed that all of these samples contained a relatively diverse microbial population (Figure 2). The similarities and differences between these populations are statistically evaluated using principal components analysis

(PCA)<sup>1</sup> (Figure 4). The fatty acid profile for sample OW-07 contained high proportions of biomarkers typically found in *Actinomyces* (particularly 10me18:0).

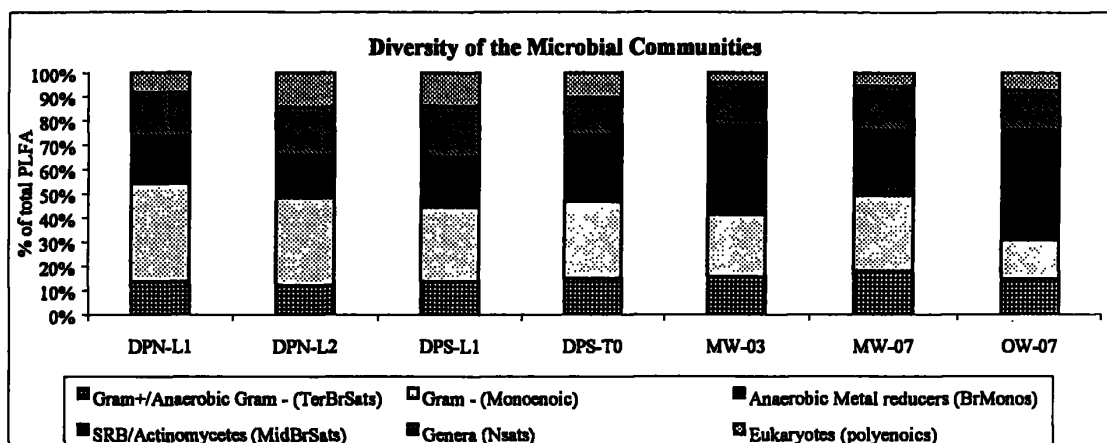


Figure 2. Diversity of the microbial communities.

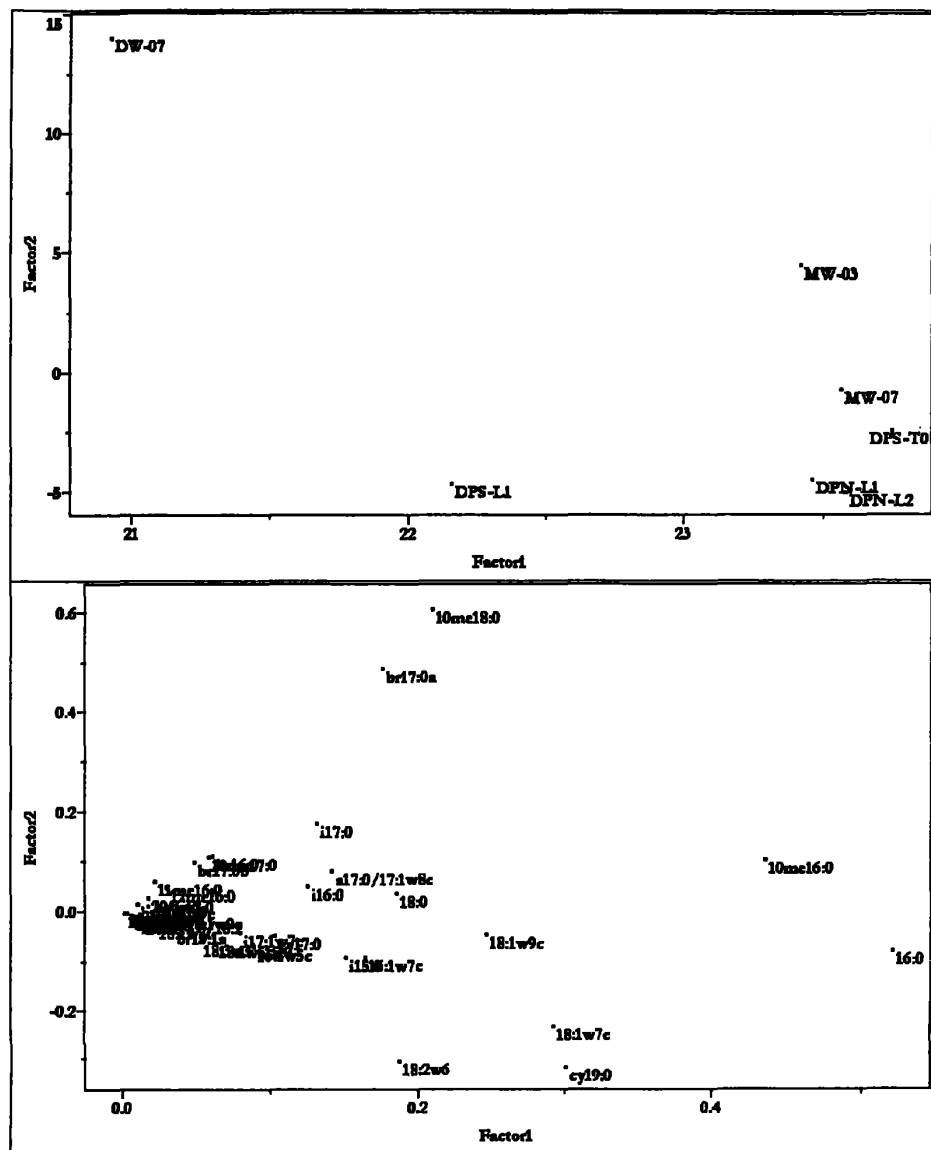
Conversely the remaining samples were primarily composed of Gram negative bacteria. Additionally, these samples contained higher proportions of 10me16:0, commonly found in anaerobic metal reducing bacteria, suggesting the presence of more anaerobic populations. Environments with more 10me16:0 than 10me18:0 typically feature anaerobic Gram negative sulfate/metal reducing bacteria.

The microbial communities from samples taken within the plume also contained higher proportions of eukaryotic PLFA. Specifically, the biomarker 18:2ω6, prominently found in fungi but also found in algae protozoa and other higher organisms.

The principal components analysis in Figure 3 shows that the microbial communities in samples OW-07 and DPS-L1 are very different from the remaining samples. As stated above, OW-07 has more *Actinomyces* biomarkers (10me18:0 and br17:0a) while DPS-L1 contains more 18:1ω7c and cy19:0 (typical of a anaerobic Gram negatives). The remaining samples had similar profiles (large amounts of 10me16:0/sulfate/metal reducers) and therefore clustered together.

<sup>1</sup> Principal components analysis (PCA) is built on the assumption that variation implies information, in the same way that HCA is built on the assumption that small multivariate distance implies similarity. Principal components analysis projects the multivariate data (PLFA profiles) onto a reduced number of dimensions (principal components) thereby simplifying the data so relationships between sample sets can easily be observed. Thus, PCA analysis can show which microbial communities are similar.





**Figure 3. Principal components analysis.**

## METABOLIC STATUS

The lipid composition of microorganisms is a product of metabolic activity and thus reflects the phenotypic response of the organisms to their environment. The physiological status of Gram-negative communities can be assessed from ratios of different monoenoic biomarkers. Specifically, 16:1 $\omega$ 7c and 18:1 $\omega$ 7c are converted to cyclopropyl fatty acids (cy17:0 & cy19:0) as microbes move from a log to a stationary phase of growth (i.e. slowing of growth). This change is expressed in the two ratios cy17:0/16:1 $\omega$ 7c and cy19:0/18:1 $\omega$ 7c, which may vary from organism to organism or environment to environment but usually will fall within the range of 0.1 (log phase) to 5.0 (stationary phase) when summed. This ratio is inversely proportional to the turnover rate, i.e. a lower ratio infers a higher turnover rate. An increase in cyclopropyl formation also has been associated with anaerobic metabolism. Gram-negative bacteria also generate *trans* fatty acids to alter the permeability of their cellular membranes as adaptation to changes in their environment (for example the presence of petroleum hydrocarbons). Ratios (16:1 $\omega$ 7t/16:1 $\omega$ 7c and 18:1 $\omega$ 7t/18:1 $\omega$ 7c) greater than 0.1 (when summed) have been shown to indicate an adaptation to a the environment resulting in decreased cellular membrane permeability (6).

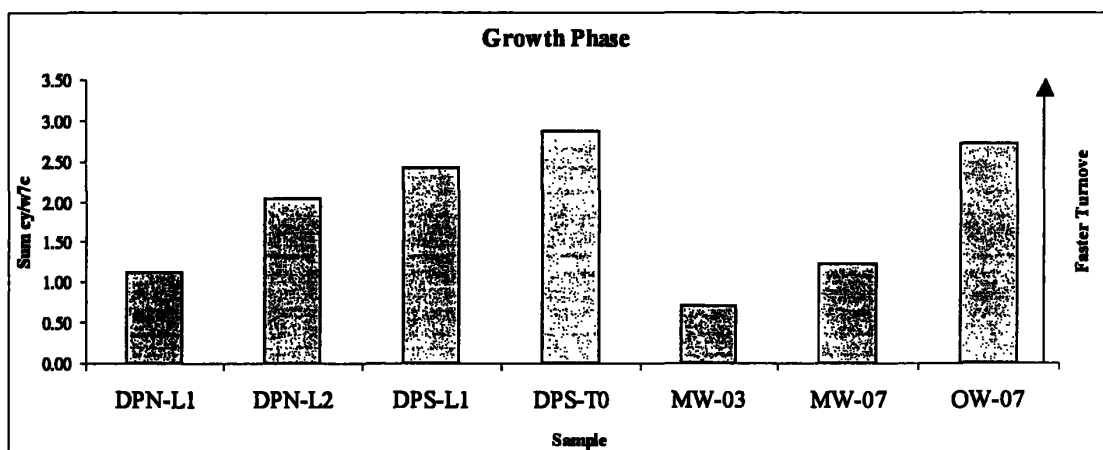
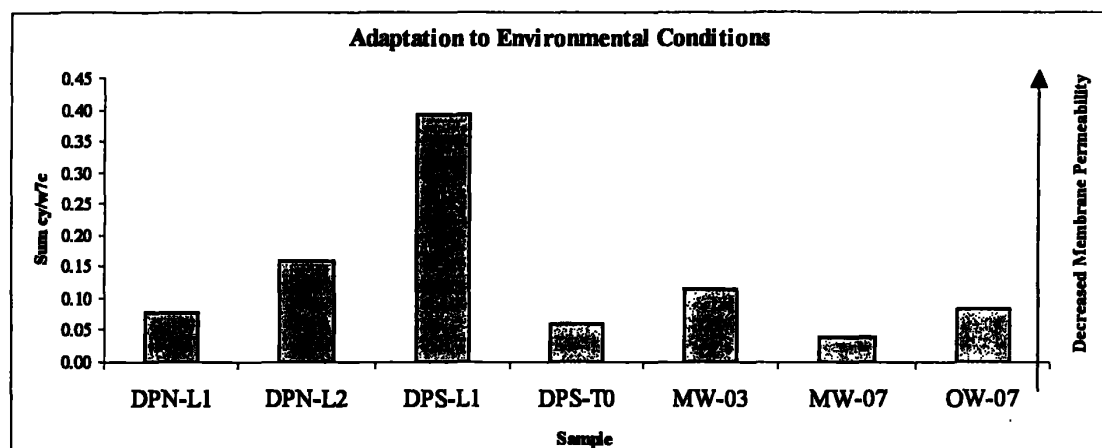


Figure 4. Growth phase of the Gram negative communities.

The Gram negative communities in all of these samples were in the stationary phase of growth, with MW-03, MW-07, and DPN-L1 having the fastest turnover rates.



**Figure 5.** Decreased membrane permeability in the Gram negative communities.

The Gram negative communities in samples DPN-L2 and DPS-L1 had decreased levels of membrane permeability (a bacterial response to environmental stress), most likely due to the Napthalene at these sites.

## REFERENCES

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Client:

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Date Received:

12/8/99

Sample Name	DPN-L1	DPN-L2	DPS-L1	DPS-T0	MW-03	MW-07	OW-07	Blank
Sample Depth	17'-19'	16'-18'	17'-19'	16'-18'	16'-18'	14'-16'	13'-15'	-
Sample Date	12/7/99	12/7/99	12/8/99	12/8/99	12/7/99	12/7/99	12/7/99	-
Wet Weight (g)	76.36	76.74	77.65	77.29	75.77	75.61	76.01	-
Moisture content (% water)	13%	13%	12%	16%	17%	15%	14%	-
Dry Weight (g)	66.09	66.46	67.99	64.81	62.82	64.19	65.28	-
MI Identifier	lkey2	lkey3	lkey7	lkey6	lkey4	lkey5	lkey1	lkey8
Total Picomoles of PLFA <sup>1</sup>	10,218	9,244	21,918	75,527	38,348	75,189	5,317	ND

**Data Summary Sheet****Biomass:**

pmols PLFA/g dry wt.	155	139	322	1,165	610	1,171	81	NC
Cells/g dry wt.	3.09E+06	2.78E+06	6.45E+06	2.33E+07	1.22E+07	2.34E+07	1.63E+06	NC
picomoles prokaryote PLFA	142	119	277	1,044	585	1,108	76	NC
picomoles eukaryote PLFA	13	20	45	121	25	64	6	NC
ratio prokaryote/eukaryote	11	6	6	9	23	17	13	NC

**Metabolic Status: (Ratio)****Growth Phase/Turnover Rate<sup>2</sup>**

cy17:0/16:1w7c	0.42	0.86	1.15	0.64	0.54	0.34	1.39	NC
cy19:0/18:1w7c	0.70	1.18	1.29	2.23	0.17	0.89	1.34	NC
Total	1.12	2.04	2.43	2.87	0.71	1.23	2.73	NC

**Environmental Stress<sup>3</sup>**

16:1w7/16:1w7c	0.05	0.11	0.07	0.00	0.05	0.00	0.00	NC
18:1w7/18:1w7c	0.02	0.05	0.33	0.06	0.06	0.04	0.08	NC
Total	0.08	0.16	0.39	0.06	0.12	0.04	0.08	NC

**Community Structure: (% of Total PLFA)**

Gram+/srb (TerBrSats)	13.8	12.2	13.7	14.9	15.6	17.9	14.8	0.0
Gram - (Monoenoic)	40.4	36.2	30.7	31.8	25.5	31.5	15.9	0.0
SRB (BrMonos)	2.9	2.5	4.4	2.9	2.5	4.1	1.2	0.0
SRB/Actinomycetes (MidBrSats)	16.6	15.4	16.6	24.7	34.7	22.7	44.4	0.0
Genera (Nsats)	18.1	19.4	20.6	15.3	17.6	18.3	16.5	0.0
Eukaryotes (polyenoics)	8.2	14.4	14.0	10.4	4.1	5.5	7.2	0.0

<sup>1</sup> method Modified Bligh & Dyer: Detection limit 50 pmols total PLFA<sup>2</sup> ratios < 0.1 log phase, 0.1 to 5.0 Stationary Phase, > 5.0 Decline Phase<sup>3</sup> ratios > 0.1 adapting to environmentally induced stress

NA: Not Analyzed NC: Not Calculated ND: Not Detected



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Sample Name	DPN-L1	DPN-L2	DPS-L1	DPS-T0	MW-03	MW-07	OW-07	Blank
Sample Depth	17'-19'	16'-18'	17'-19'	16'-18'	16'-18'	14'-16'	13'-15'	-
Sample Date	12/7/99	12/7/99	12/8/99	12/8/99	12/7/99	12/7/99	12/7/99	-
Wet Weight (g)	76.36	76.74	77.65	77.29	75.77	75.61	76.01	-
Moisture content (% water)	13%	13%	12%	16%	17%	15%	14%	-
Dry Weight (g)	66.09	66.46	67.99	64.81	62.82	64.19	65.28	-
MI Identifier	lkey2	lkey3	lkey7	lkey6	lkey4	lkey5	lkey1	lkey8
Total Picomoles of PLFA <sup>1</sup>	10,218	9,244	21,918	75,527	38,348	75,189	5,317	ND

**Analytical Report**

[REDACTED]

## Equivalent Chain Length

**Terminally Branched Saturates (TerBrSats)**

i14:0	13.62	0.0	0.1	0.3	0.1	0.1	0.2	0.0	0.0
i15:0	14.63	3.0	2.6	4.4	3.6	3.6	5.6	1.2	0.0
a15:0	14.70	2.2	1.9	2.3	2.1	2.1	2.9	0.6	0.0
i16:0	15.63	2.8	2.4	2.5	3.0	3.3	2.9	3.2	0.0
i17:0	16.62	2.6	2.3	2.0	2.9	2.8	2.9	5.7	0.0
a17:0/17:1w8c	16.70	<u>3.2</u>	<u>2.8</u>	<u>2.2</u>	<u>3.3</u>	<u>3.7</u>	<u>3.4</u>	<u>4.0</u>	<u>0.0</u>
		13.8	12.2	13.7	14.9	15.6	17.9	14.8	0.0

**Monoenoics (Monos)**

16:1w9c	15.69	0.8	0.7	0.9	0.9	1.3	1.6	0.5	0.0
16:1w7c	15.75	5.0	3.6	2.7	3.3	5.3	5.1	1.0	0.0
16:1w7t	15.78	0.3	0.4	0.2	0.0	0.3	0.0	0.0	0.0
16:1w5c	15.83	2.8	1.8	1.5	1.8	2.3	3.5	0.3	0.0
16:1w13t	15.90	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0
cy17:0	16.80	2.1	3.1	3.1	2.1	2.9	1.7	1.3	0.0
18:1w9c	17.69	8.6	6.2	5.7	4.3	4.3	5.1	5.5	0.0
18:1w7c	17.75	11.3	8.7	5.3	5.4	6.3	6.7	2.9	0.0
18:1w7t	17.79	0.3	0.5	1.8	0.3	0.4	0.3	0.2	0.0
18:1w5c	17.84	1.5	1.0	2.6	1.6	1.4	1.7	0.3	0.0
cy19:0	18.81	<u>7.9</u>	<u>10.3</u>	<u>6.9</u>	<u>11.9</u>	<u>1.1</u>	<u>6.0</u>	<u>3.9</u>	<u>0.0</u>
		40.4	36.2	30.7	31.8	25.5	31.5	15.9	0.0

**Branched Monoenoics (BrMonos)**

i15:1	14.35	0.0	0.0	0.2	0.0	0.0	0.1	0.0	0.0
br15:1a	14.41	0.0	0.0	0.2	0.0	0.0	0.1	0.0	0.0
i16:1a	15.34	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0
i16:1b	15.41	0.3	0.3	0.1	0.2	0.3	0.3	0.0	0.0
i17:1w7c	16.34	1.9	1.5	1.5	2.2	1.8	3.0	0.7	0.0
br19:1a	18.03	<u>0.7</u>	<u>0.7</u>	<u>2.4</u>	<u>0.4</u>	<u>0.4</u>	<u>0.4</u>	<u>0.5</u>	<u>0.0</u>
		2.9	2.5	4.4	2.9	2.5	4.1	1.2	0.0

**Mid-Chain Branched Saturates (MidBrSats)**

10me14:0	14.46	0.0	0.0	0.2	0.0	0.0	0.1	0.0	0.0
br15:0	15.08	0.2	0.1	0.2	0.2	0.3	0.3	0.4	0.0
br15:0	15.48	0.2	0.1	0.2	0.2	0.3	0.3	0.4	0.0

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Sample Name	DPN-L1	DPN-L2	DPS-L1	DPS-T0	MW-03	MW-07	OW-07	Blank
Sample Depth	17'-19'	16'-18'	17'-19'	16'-18'	16'-18'	14'-16'	13'-15'	-
Sample Date	12/7/99	12/7/99	12/8/99	12/8/99	12/7/99	12/7/99	12/7/99	-
Wet Weight (g)	76.36	76.74	77.65	77.29	75.77	75.61	76.01	-
Moisture content (% water)	13%	13%	12%	16%	17%	15%	14%	-
Dry Weight (g)	66.09	66.46	67.99	64.81	62.82	64.19	65.28	-
MI Identifier	lkey2	lkey3	lkey7	lkey6	lkey4	lkey5	lkey1	lkey8
Total Picomoles of PLFA <sup>1</sup>	10,218	9,244	21,918	75,527	38,348	75,189	5,317	ND
br16:0	16.07	1.0	0.9	1.0	1.5	1.2	3.2	0.0
10me16:0	16.43	7.2	7.0	8.9	12.0	15.4	11.7	0.0
11me16:0	16.47	0.7	0.0	0.0	0.0	2.0	0.0	0.0
12me16:0	16.52	0.5	0.4	0.3	0.8	1.4	0.5	0.0
br17:0a	17.05	2.1	2.2	1.9	3.7	4.1	3.3	0.0
br17:0b	17.11	0.7	0.7	0.7	1.2	1.2	0.8	0.0
10me17:0	17.41	0.9	1.0	1.1	0.9	1.8	1.0	0.0
12me17:0/18:2	17.47	0.2	0.2	0.5	0.2	0.2	0.2	0.0
10me18:0	18.38	2.3	2.9	1.8	3.9	6.4	3.5	0.0
12me18:0	18.43	<u>0.8</u>	<u>0.0</u>	<u>0.0</u>	<u>0.2</u>	<u>0.3</u>	<u>0.0</u>	<u>0.0</u>
		16.6	15.4	16.6	24.7	34.7	22.7	44.4
Normal Saturates (NSats)								
12:0	12.00	0.0	0.0	0.1	0.0	0.0	0.0	0.0
14:0	14.00	0.2	0.3	0.6	0.2	0.3	0.5	0.0
15:0	15.00	0.4	0.4	0.8	0.4	0.5	0.5	0.0
16:0	16.00	12.7	13.7	12.0	10.2	12.3	13.1	9.7
17:0	17.00	0.7	0.9	0.9	0.9	1.1	0.7	1.2
18:0	17.98	<u>4.0</u>	<u>4.1</u>	<u>6.2</u>	<u>3.7</u>	<u>3.4</u>	<u>3.5</u>	<u>2.3</u>
		18.1	19.4	20.6	15.3	17.6	18.3	16.5
Eukaryotes								
18:2w6	17.59	3.7	6.6	8.9	6.7	1.3	1.9	1.0
18:3w3	17.63	0.8	2.5	1.8	1.9	0.4	0.4	0.7
20:4w6	19.19	0.4	0.7	0.3	0.2	0.3	0.8	0.5
20:3w6	19.38	0.2	0.6	0.3	0.2	0.4	0.4	0.9
20:2w3	19.60	0.0	0.1	0.0	0.1	0.0	0.1	0.0
20:1w11c	19.66	0.2	0.0	0.0	0.0	0.0	0.0	0.0
20:1w9c	19.68	0.3	0.7	0.4	0.4	0.4	0.6	0.8
20:0	20.00	0.9	1.1	0.6	0.5	0.5	0.5	1.3
22:0	22.00	0.9	1.1	1.0	0.4	0.5	0.4	1.2
23:0	23.00	0.4	0.4	0.4	0.0	0.2	0.2	0.2
24:0	24.00	<u>0.5</u>	<u>0.6</u>	<u>0.4</u>	<u>0.2</u>	<u>0.2</u>	<u>0.3</u>	<u>0.7</u>
		8.2	14.4	14.0	10.4	4.1	5.5	7.2

PROJECT REFERENCE <b>BEAZER SOUTH CAVALCADE</b>		PROJECT NO <b>99-785</b>		P.O. NUMBER		MATRIX TYPE		REQUIRED ANALYSES										PAGE 1 OF 1			
PROJECT LOC. (State) <b>TX</b>		SAMPLER(S) NAME <b>R. DELISTO</b>		PHONE <b>(412) 279-3363</b>		FAX <b>(412) 279-4332</b>		<div style="display: flex; justify-content: space-around;"> <div style="writing-mode: vertical-rl; transform: rotate(180deg);">AQUEOUS (WATER) SOLID OR SEMISOLID AIR</div> <div style="writing-mode: vertical-rl; transform: rotate(180deg);">NONAQUEOUS LIQUID (or solvent etc)</div> <div style="writing-mode: vertical-rl; transform: rotate(180deg);">PLFA</div> <div style="writing-mode: vertical-rl; transform: rotate(180deg);">PAH GENE PAGE</div> </div>													
CLIENT NAME <b>KEY ENVIRONMENTAL</b>				CLIENT PROJECT MANAGER <b>JIM ZUBROW</b>																	
CLIENT ADDRESS (CITY, STATE, ZIP) <b>1200 ARCH ST, CARNEGIE, PA 15106</b>																					
SAMPLE		SL NO.		SAMPLE IDENTIFICATION				NUMBER OF CONTAINERS SUBMITTED										REMARKS			
DATE	TIME																				
<b>12/1/99</b>	<b>0835</b>			<b>OW - Q7 (13'-15')</b>				<b>X</b>	<b>X</b>	<b>X</b>											
	<b>0835</b>			<b>DPN - L1 (17'-19')</b>				<b>X</b>	<b>X</b>	<b>X</b>											
	<b>0918</b>			<b>DPN - L2 (16'-18')</b>				<b>X</b>	<b>X</b>	<b>X</b>											
	<b>1000</b>			<b>MW - Q3 (16'-18')</b>				<b>X</b>	<b>X</b>	<b>X</b>											
<b>✓ 1021</b>				<b>MW - Q7 (14'-16')</b>				<b>X</b>	<b>X</b>	<b>X</b>											
RELINQUISHED BY: (SIGNATURE)		DATE		TIME		RELINQUISHED BY: (SIGNATURE)		DATE		TIME		RELINQUISHED BY: (SIGNATURE)		DATE		TIME					
		<b>12/1/99</b>		<b>1830</b>																	
RECEIVED BY: (SIGNATURE)		DATE		TIME		RECEIVED BY: (SIGNATURE)		DATE		TIME		RECEIVED BY: (SIGNATURE)		DATE		TIME					
<b>FEDER 815217929617</b>		<b>12/1/99</b>		<b>1830</b>																	
LABORATORY USE ONLY																					
RECEIVED FOR LABORATORY BY: (SIGNATURE)				DATE		TIME		CUSTODY INTACT		CUSTODY SEAL NO.		SL LOG NO.		LABORATORY REMARKS:							
								<input type="checkbox"/> YES <input type="checkbox"/> NO													

ORIGINAL

serial number 146045



## ANALYSIS REQUEST AND CHAIN OF CUSTODY RECORD

# MICROBIAL INSIGHTS

- ☐ 5102 LaRoche Avenue, Savannah, GA 31404  
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